Managing for Climate Resilience

on The Nature Conservancy Preserves and Managed Lands in the Eastern United States

Guidance for Land Managers at The Nature Conservancy

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The Nature Conservancy
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Managing for Climate Resilience on The Nature Conservancy Preserves and Managed Lands in the eastern United States.

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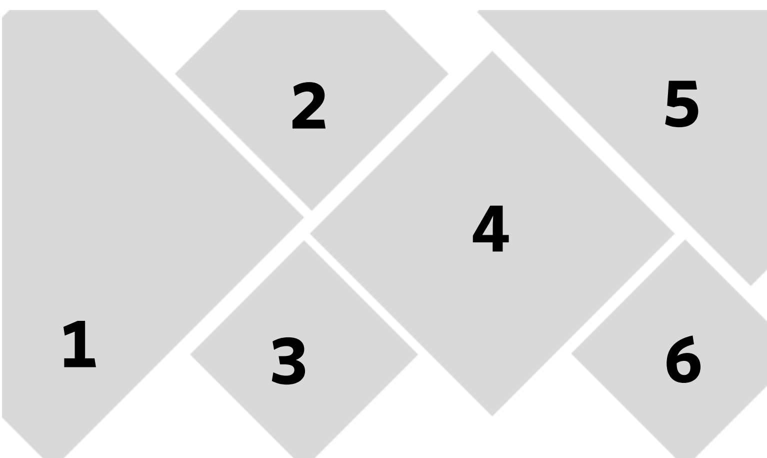

About the Cover:

1. Rich Northern Hardwood Forest in Vermont. Calcareous bedrock, topographic complexity, and colluvial processes produce a local hotspot for biodiversity that can be managed for climate resilience. © Gustave Goodwin

2. Bog laurel. © Gustave Goodwin

3. Refugio-Goliad Prairie which spans 500,000 acres along the Gulf Coast between Houston and Corpus Christi. It is one of the largest and highest-quality expanses of coastal tallgrass prairie remaining in Texas. Although some native species have declined and even disappeared from the region, great biological diversity still thrives, making landscape-scale work possible.. © Kenny Braun

4. Old logging scar in yellow birch. © Gustave Goodwin

5. Moehringia Macrophylla. © Gustave Goodwin

6. © Gustave Goodwin

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Many individuals have contributed to this project over the years, and it is impossible to fully capture the unique roles that each person has played. We hope that the table below serves as an initial acknowledgment of their positive contributions.

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What is this document designed to achieve?

What this guidance *is:*	What this guidance *is not*:
A resource designed for those involved in TNC's land management strategies. Land managers, scientists, and program directors are target audiences for this guidance, which poses questions in an open framework to incorporate into existing management and conservation strategies. This guidance should help bridge the gap between the use of the Resilient Sites Analysis and land management.	**A step-by-step guide for land management** This guidance is not intended to prescribe actions at the site level. Instead, it seeks to equip land managers and conservation programs with a framework that can be used to develop strategies and prioritize actions that address landscape and site level concerns. Additionally, it assumes the reader is familiar with the context of land management, planning, and monitoring.
Focused on the science and ecosystems of the eastern United States. This guidance was specifically designed for TNC's Northeast, New York, and Southern Divisions. There are many important ecoregional considerations that are not covered in this document, but the aim of the document is to provide a framework.	**A source for science from outside the eastern United States.** While some of the information in this guidance may apply to ecosystems found in the rest of the country, no attempt was made to summarize or denote where other ecoregional contexts are similar or different.
An initial compilation and synthesis of actionable research. This guidance is the first compilation of existing knowledge and information. New examples and research will emerge, and the community of practice in TNC should continue to use the best available science.	**Static information** This guidance should not be considered static or authoritative. New science and research will become available. We hope this framework will catalyze a community of practice and knowledge exchange within TNC and its partners.
A framework for considering resilience to climate change impacts in the context of land management norms and stressors. The guidance will complement Divisional protection plans and help refine future iterations.	**A general synthesis of climate change impacts for the eastern United States.** This information is widely available and familiar to many land managers. What is less familiar is how to translate this information to improve management of lands and waters.

1) Introduction

"The furnaces of the world are now burning about 2,000,000,000 tons of coal a year. When this is burned, uniting with oxygen, it adds about 7,000,000,000 tons of carbon dioxide to the atmosphere yearly. This tends to make the air a more effective blanket for the earth and to raise its temperature. The effect may be considerable in a few centuries."
-Science News and Notes, RODNEY AND OTAMATEA TIMES, WAITEMATA AND KAIPARA GAZETTE, 14 AUGUST 1912.

"There's one issue that will define the contours of this century more dramatically than any other, and that is the urgent threat of a changing climate."
-President Barack Obama, U.N. Climate Summit, 2014.

"Sometimes I look at all these climate model predictions and think the greatest source of uncertainty is what are we going to do about it."
-Anonymous comment, Forest Ecosystem Monitoring Cooperative Annual Meeting, 2019.

Objective

This document will inform The Nature Conservancy's land managers on how to incorporate principles of climate resilience into the management of terrestrial systems. This guidance promotes shared principles for adapting land management in an uncertain future of climate change in order to ensure a world where nature and people thrive. Our hope is that this document spurs a robust discussion.

Why is this document important? Why do TNC land managers need it now?

To guide action on the most important resilient sites under TNC management.
TNC North America has embraced the concept of "Conserving Nature's Stage," which has been identified for the U.S. through the Resilient Sites analysis. The Resilient Sites analysis identifies lands with the geophysical properties, sources of biodiversity, and ecological connections that may buffer the impacts of climate change on our natural systems. This map, and the science used to develop it, lays the foundation for TNC's strategy to conserve and manage resilient sites and systems in North America.

Because using the same approaches to land management won't work as the climate changes.
A rapidly changing climate will bring additional stress to lands and waters already facing a host of related challenges, such as invasive species, over-browsing, and land-use legacies, that will themselves be exacerbated by climate change. In the past, land

management and restoration approaches tended towards protecting or recreating historical site conditions. The changes to ambient conditions (temperature, moisture, timing) brought by climate change will fundamentally shift sites away from the historical condition, diminishing the utility of this management approach. Instead, managers must emphasize management that will bolster the resilience of sites and systems to climate and other environmental changes allowing for species and habitats to adapt.

To define and outline what improved management means in the context of climate-resilient lands.
Management of terrestrial ecosystems is a critical component of TNC's Shared Conservation Agenda, with "hectares with improved management" identified as a key outcome metric in our 2030 goals. It is important to define and outline climate-informed strategies for land management and ecological protection and/or restoration of the resilient and connected network. Stewardship staff should be working with Protection staff to identify lands that contribute to resilience at the preserve scale.

Because TNC is a recognized leader on science and ecosystem management.
Building upon TNC's track record and expertise in land management will provide us a seat at the table in discussions on climate change action as well as credibility as we seek to collaborate with and empower others to manage their lands for resilience.

2) Core Principles: Managing for Climate Resilience

As land managers, we play an important role in confronting the direct impacts of a rapidly changing global climate on our local landscapes. The lands we own and manage are, and will continue to be, influenced by changes in climate that will compound existing stresses and introduce new challenges. We are faced with considerable uncertainty about the direction and magnitude of future impacts and must adjust our management approach to accommodate this new reality. Traditional ecosystem management, with its emphasis on historical reference conditions and threat abatement, is not designed to address this level of uncertainty or the abundance of climate-related threats which cannot be managed at the site, or even system, level.

> ***Instead, we must accept that** our sites will change **and we must shift our focus towards fostering their future diversity and function, intrinsic adaptive capacity, and connectivity at the landscape level.***

This philosophy lies at the core of the analysis presented in Resilient and Connected Landscapes for Terrestrial Conservation (Anderson et al. 2016), which identifies a network of lands with the physical properties and landscape connections that may buffer the impacts of climate change by giving species the room to move and adapt. This analysis provides land managers with a scientific framework for evaluating the inherent resilience of their sites and the role those sites play in the larger landscape. Just as importantly, it provides a shared vocabulary that can be used to define desired outcomes across the vast array of lands that fall under TNC management. These include:

- *Resilience*: capacity of a geophysical site to maintain species diversity, productivity, and ecological function as the climate changes

- *Resilient Site*: a structurally intact geophysical site that sustains a diversity of species and natural communities, maintains basic relationships among ecological features, and allows for adaptive change in biotic community composition and structure

- *Resilient System*: a biotic community that exhibits adaptive capacity to sustain its diversity, function, and services despite exposure to disturbance and climate change. (Modified from Anderson et al. 2016)

Based on the definitions above, we propose the following definition for managing for climate resilience in terrestrial systems (herein terrestrial resilience):

> ***Managing for climate resilience****: an adaptive management process that maintains the resilience of and/or improves the ability of a terrestrial system in adapting to a changing climate.*

The science that underlies existing management paradigms, such as the natural community concept, historic range of variability, or managing towards reference conditions, are essential for understanding how sites may change in the future and what, if anything, we wish to do to facilitate desirable changes. We believe that resilient sites and systems, as defined above, provide an appropriate framework for developing site and system specific goals and for the honest assessment of those goals in a rapidly changing climate. This is consistent with the working definition of Land Area with Improved Management that will be used to track progress towards TNC's Shared Conservation Agenda 2030 Goals — "a spatially-defined area whether protected or unprotected, public, private, or communal, that is moved towards or maintained at a desired ecological condition" (Lands Measures Advisory Group 2021). Area with improved management is designed to capture the land area (e.g., entire project area) that is estimated to be improved over a given timeline by a suite of management activities that, collectively, result in persistent systemic change.

Although the definition of managing for resilience is broad, we propose that there are universal principles that will guide its implementation across a diversity of lands and are asking that we, as land managers, commit to the following principles:

- ***Manage the Stage****:* The *Resilient and Connected Landscapes for Terrestrial Conservation* report provides a framework for identifying the links between biodiversity and the geophysical properties of a given site (Anderson et al. 2016). These geophysical properties, often referred to as Nature's Stage, are a critical component of site resilience and should be considered a primary management concern. Some properties, such as bedrock chemistry or landscape form, are impossible to manage, but others, such as hydrology, soil, and structural connectivity may be viable management objectives. Given the fundamental role that these geophysical properties play in sustaining current and future biodiversity, we encourage land managers to consider restoring Nature's Stage as a prerequisite to actions designed to foster resilient systems.

- ***Expect and Manage for Transition***: The sudden availability of space and resources resulting from extreme events often leads to system transition, and changes in the ambient temperature and moisture make it unlikely that systems will return to exactly what they were before. To maintain diverse and productive ecosystems, our aim is to manage these transitions so species can persist, move, or adapt depending on their individual responses.

- ***Anticipate New Impacts, but Attend to Existing Stresses***: Adaptive management plans should account for both climate and non-climate factors where evidence suggests that these threats or stressors are likely to interact synergistically with, or be exacerbated by, climate change. We should focus management on stressors that impact aspects of site resilience and are tied directly to key elements that enhance system resilience (such as species diversity or key ecological processes). We should avoid managing stressors limited to maintaining a particular community type.

- ***Work with Natural Processes***: Studies suggest that the more we work with natural processes, the greater success we will have in sustaining diversity (Fei et al. 2017; Heller & Zavaleta 2009). When possible, we should design interventions that will both restart a natural process, such as recruitment or burning, and create the conditions for self-perpetuation. There are several benefits to this approach. First, it is sound ecosystem management. Second, it offers the possibility of limiting the need for future interventions. And lastly, it is a viable approach for addressing uncertainty and spreading risk.

- ***Adopt Multiple Strategies***: Adopting multiple strategies is an important approach to spreading risk, confronting uncertainty, and identifying successful actions. While this is considered a principle in its own right, it also serves as a reminder that any of the above principles can incorporate multiple strategies. Strategies can be organized into the three categories: 1) options- those that allow for species to adjust, change, or avoid risk, 2) processes - those that reverse abiotic degradation or restore processes, and 3) sources- those that sustain the sources of biotic response. Considering this range of strategies can help managers identify a comprehensive approach to managing for resilience. These categories (modified from Gunderson 2000) are further explored in Appendix C.
    - **Options** refer to strategies that distribute risk or that provide opportunities and alternatives for species. Many traditional conservation strategies fall into this group such as increasing the size of a reserve to accommodate disturbances, or increasing habitat connectivity, so species can move in response to climate change.
    - **Processes** refer to strategies that maintain or restore the condition of the physical and chemical stage and its cycles of material and energy transport. These strategies aim to prevent or reverse degradation such as poor water quality or reduced soil fertility, and to create the conditions under which the biota can thrive.
    - **Sources** refer to strategies that conserve or increase the biotic features that provide raw material for adaptation and community adjustments to shifting ambient conditions or changing disturbance regimes.

- ***Adapt***: Management for terrestrial resilience is an iterative process, requiring continued monitoring and evaluation. This is true for all levels of the management process, from evaluating the consequences of individual actions, to redefining goals, and prioritizing resources at and among sites. The adaptive management process should be driven by the best available data.

- ***Take the Plunge*:** The time to begin is now. While the uncertainties and challenges of managing sites and systems in a changing climate are daunting, the need to act is pressing. We encourage land managers to set aside the expectation that they will identify an exact solution for their site and instead focus on a reasonable and defensible starting point for taking action. The above principles can help identify those actions, but is also important that our actions represent our organizational values and responsibilities to the communities that we serve. To that end, we ask land managers to also include these commitments in their management process:

- We are *committed* to promoting a culture of learning and knowledge sharing to unify and leverage our collective efforts and empower others to take action.
- We are *committed* to managing our lands to enhance climate resilience at a meaningful scale by working with partners to take a landscape approach.
- We are *committed* to managing our lands to achieve cross-cutting objectives for the benefit of both nature and people.

3) Laying Important Groundwork

While the intent of this document is to help land managers implement site-specific actions to increase climate resilience of natural systems, we recognize that there are critical dimensions that may be more effectively considered at other scales or as separate processes. In this section, we raise some of these issues and, where possible, direct managers to resources that may assist them in addressing them.

This section contains three parts. They lay the groundwork for the adaptive management cycle, which is detailed in the next section.

3.1. Socio-ecological Considerations
3.2. Site and Strategy Prioritization
3.3. Assisting Nature: Introducing and transporting species to facilitate adaptation

Section 3.1: Socio-ecological Considerations

The first key advance of Conservation by Design 2.0 (CbD 2.0) is the explicit recognition that social and natural systems are deeply interconnected. There are no natural systems without some form of human influence, and no social systems without nature. Conservation must honor this inseparable relationship. Across its conservation work, TNC seeks to transform 'the relationship between people and nature to a more positive one, and to strengthen existing positive relationships', by prioritizing 'conservation solutions that both benefit nature and improve people's lives.' TNC also recognizes that there will be times and places where the needs of people and nature will be in conflict and that we may choose to protect nature for its intrinsic value, even if there is no obvious or immediate material or economic benefit to people.

In many regards, this is familiar territory for land managers at TNC. Our lands and waters are among the most visible and tangible products of our conservation work and are a key point of interaction with the public. They are a primary driver of TNC's website traffic, with one in every five users visiting a preserve page (LOL Narrative 4.0). As a result of our long history of land acquisition and management, TNC land managers are generally well equipped to manage for multiple socio-ecological values, identify and minimize conflicts, and elevate positive messages around conservation related to land and water protection. Across TNC, many of these interactions are governed by our SOPs. In many state programs, Stewardship and Visitor Use Polices (or a comparable policy) inform the interactions between people and nature across TNC managed lands and provide a framework for addressing the unique challenges and opportunities provided by individual sites.

We encourage land managers to take a fresh look at socio-ecological interactions at our managed areas through the lens of climate resilience. Are there actions, existing or possible, that can enhance the ecological resilience of a site while providing benefits to people? Do people value the benefits provided by an action? What are the impacts of a proposed action on people? What are the impacts of inaction on people? Are there existing socio-ecological interactions that degrade the resilience of a site? Are people aware of the consequences of that interaction? While most of these considerations are inherently local and best addressed on a site-by-site basis, there are some considerations that will be most effectively handled through a separate process or at a different scale. These include:

- Revisit existing policies and plans that guide management of TNC lands and waters to ensure they adequately consider climate change and its impacts on socio-ecological interactions.

- Strengthen collaboration between land managers and other departments within TNC. An internal review of TNC lands concluded that our nationwide network of protected lands and waters provides us with "irreplaceable credibility" with the public, our partners, and our donors (LOL Narrative 4.0). To take full advantage of this credibility, our land management should inform, and be informed by, our science, policy, and communications agendas. At a minimum, land managers should advocate that our network of protected lands and waters play a central role in communicating the benefits of conservation for people and nature, across a wide range of benefits.

- Directly connect management to TNC's organization-wide efforts to elevate diversity, equity, inclusion, and justice (DEIJ) in conservation. Our lands and waters are a focal point for interaction with the public and, in some cases an enduring legacy of disposition and removal of marginalized people, making this is an essential issue for land managers. TNC's Indigenous Peoples and Local Communities program has developed resources and networks that may be useful to managers. The Indigenous Peoples Burning Network provides an interesting model for collaboration between tribes and land managers that yields cultural and ecological benefits. As TNC ventures deeper into this body of work, we expect that land managers will be provided with additional resources to facilitate the inclusion of DEIJ principles in designing and implementing management. At a minimum, managers should use the social safeguard questions, identified in CbD 2.0 to evaluate TNC-led management actions across multiple scales.

Section 3.2: Site and Strategy Prioritization

Given the wide variability in site conditions and stressors across lands owned or managed by TNC, it is unlikely that all will need to be managed for climate resilience or that TNC will have the capacity to do so, even at sites with demonstrated need for intervention. Therefore, prioritization is critical for identifying where management actions are essential for resilience and where intervention will result in lasting or systemic change that improves long-term resilience. TNC practitioners already face multiple challenges and demands, and in many instances resort to a triage model in making decisions on how to allocate management resources. A site prioritization framework for management will allow managers to best allocate their limited resources for maximum conservation benefit and contribution toward the SCA goals.

A prioritization framework can be simple or complex, depending upon the portfolio of lands under consideration, the strategies available, and other programmatic objectives. Regardless of the complexity of the prioritization effort, it is likely to draw heavily upon spatial data, and should yield spatially explicit actions (Spatial Action Mapping). The integration of spatial data with strategy development and selection is the third key advance of CbD 2.0.

In July 2020, a team was assembled to create a more user-friendly version of CbD 2.0 that could be applied consistently by TNC staff across programs. Products are expected as early as 2022. In the meantime, we recommend considering a range of values identified by CbD 2.0 to inform a prioritization process that is appropriately scaled to the resources and opportunities available for management. These values include: the quality of the lands and waters (assets); the risks and threats that face the assets; the net benefits of a given action or strategy; the feasibility of a given strategy or action; and the return on investment of that strategy or action. Examples of how these values might inform site and strategy prioritization in the context of the lands TNC owns and manages are presented below.

Value	Example
Asset	• Prioritization of TNC lands identified as part of the Resilient and Connected Network • Prioritization of lands with unique biodiversity or attributes that are not adequately protected and managed for climate resilience within the ecoregion
Risks and Threats	• Prioritization of lands where invasive species pressure threatens important species or ecosystem functions and management success is likely • Prioritization of lands with low or minimal threats in a changing climate
Net Benefits	• Prioritization of TNC lands and waters where TNC's actions can contribute to a larger landscape (e.g., statewide) management strategy or initiative • Prioritization of lands with multiple benefits such as biodiversity protection, carbon storage, and source water conservation.
Feasibility	• Prioritization of actions at sites where sufficient resources are available to ensure project completion

Return on Investment	• Prioritization of actions or sites where management of isolated or incipient stressors will result in lasting or systemic change

Section 3.3: Assisting Nature: Introducing and transporting species to facilitate adaptation

The core principles of managing for climate resilient sites explicitly include allowing "for adaptive change in biotic community composition and structure." Naturally, this raises questions about the extent to which land managers should facilitate this change through a variety of actions generally described as assisted migration. With fragmented habitats that restrict species dispersal and a rapidly changing climate that may outpace natural dispersal rates, there is a compelling argument for land managers to intervene and intentionally translocate species or genetic material to more suitable ranges. There is also a long track record of success with this strategy. A recent study of conservation translocations in the United States, spanning 125 years, found that with adequate conservation practice and regulation, "conservation translocations routinely yielded their intended benefits without producing unintended harm" (Novak et al. 2021). Yet, the abundance of invasive species, many intentionally introduced, serves as a stark reminder about the difficulty of anticipating the results of manipulations into complex, highly connected systems and demand a cautious, humble approach to the topic.

At this time, TNC does not have consistent guidance about assisted migration and the authors are unaware of existing resources within TNC to support land managers in deciding when, how, or where to take action. Until such guidance exists, individual states should continue to rely upon the best available science, local context and partner attitudes, and site-based knowledge to make decisions about assisted migration. TNC scientists and land managers have generally taken a relatively cautious approach to assisted migration, favoring movement of species from one location to another within its existing range.

We recommend that individual chapters or programs address assisted migration as a separate process from site-level resilience planning, ideally producing a decision tree that can be used by land managers. This should allow for a comprehensive review of strategies for assisted migration, many of which are low risk and fairly benign, and when and where such actions may be appropriate. An established framework for making decisions about assisted migration is valuable for land managers because it streamlines the planning process and reduces the pressure and risk associated with letting individual projects set precedent or drive policy.

One such framework that may be helpful for TNC land managers was developed by the Vermont Agency of Natural Resources to guide implementation of assisted migration strategies on Agency lands (Assisted Migration Work Group 2017). It contains helpful and concise summaries of strategies for assisted migration, organizes those options into different tiers based on risk and liability, and provides guidance about when and where those actions are appropriate on state-owned land. It could readily be adopted or modified for use on lands managed by TNC.

4) The Adaptive Management Cycle

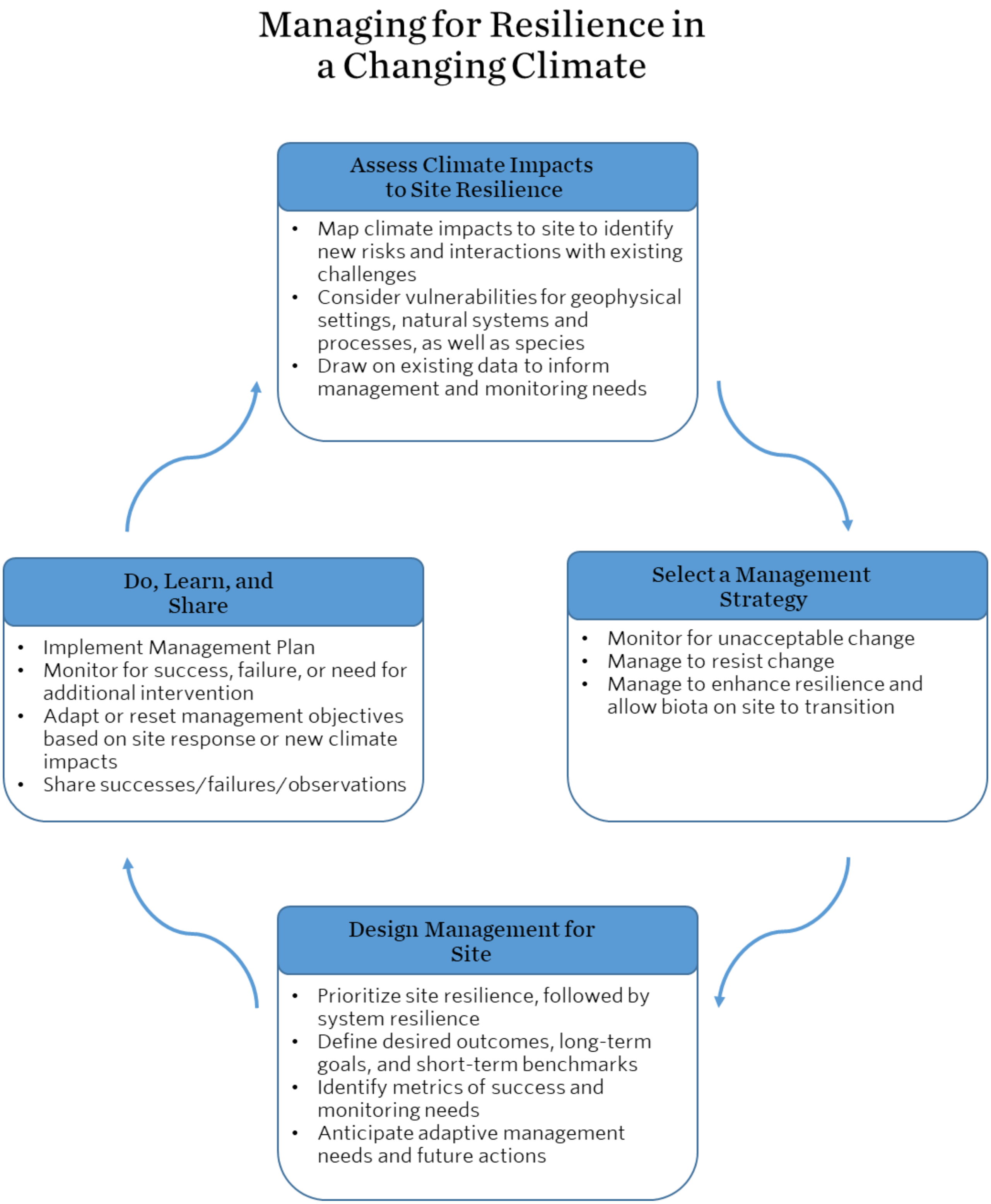
Managing for terrestrial resilience is an ongoing process, not a singular action and often not a linear series of actions. To organize this process, we have modified an adaptive management approach (Figure 4.1), detailed on the next page.

This section provides the key context for each of the four steps of the cycle:

4.1. Assess Climate Impacts to Site Resilience
4.2. Select a Management Approach
4.3. Design Management for Site
4.4. Do, Learn, and Share

Following this section, the remainder of the document is designed to provide the information, resources, case studies, and professional networks to support a land manager in using this approach to improving climate resilience of TNC managed lands.

Figure 4.1: The Adaptive Management Cycle



Section 4.1: Assess Climate Impacts to Site Resilience

Understanding the potential responses of a site or system to the changing climate is the basic foundation of managing for terrestrial resilience. The resources provided in Appendix A will help land managers in anticipating changes in key climate variables, such as temperature and precipitation, and identify potential impacts of those changes at the site or system in question.

When thinking about the effects of climate change on a site, we recommend that land managers assess the site from several different perspectives: the geophysical setting, the system, the species, the overall function of the site within its landscape context, and social and cultural considerations (also covered in Section 3). The goal of managing for resilience is to improve an ecosystem's capacity to adapt to increased disturbance and directional shifts in climate, not to prevent an ecosystem from experiencing change.

Land managers should keep in mind how exposures and vulnerabilities will interact with the site's characteristics. These exposures and vulnerabilities can be categorized under five headings:

1. ***the geophysical setting*** *(landscape topography, geology/soils, and associated abiotic conditions – including temperature and moisture)*,
2. ***the system*** *(the holistic ecological interconnections that sustain biological processes)*,
3. ***the species*** *(flora, fauna, and fungi)*,
4. ***site in a landscape context*** *(an understanding of the desired function within the overall landscape)*, and
5. ***social and cultural considerations*** *(impacts on and from people, and special consideration of marginalized communities, Tribal Nations, and other indigenous peoples).*

To help managers in evaluating resilience and prepare them to select and design a management strategy, we present a series of questions in these five categories to be used alongside the vulnerability assessment framework in the following table.

Table 4.1: Questions to assess climate impacts and determine actions to improve site resilience

Resilience Evaluation	
1. Geophysical Setting	
First, focus on managing Nature's Stage by applying practices that maintain or improve the physical site in a changing climate. This includes features such as soil composition and structure, hydro-geomorphology, and connectivity that provide an enduring foundation for biodiversity.	
Existing liabilities?	Are there existing liabilities to the geophysical condition of the site that undermine important processes (such as flooding or fire)? Do these liabilities limit the long-term ability of the site to support diverse systems and species?
New and exacerbated liabilities from climate change?	Will climate change exacerbate those liabilities? Will it create new liabilities?
Response feasibility?	Is it feasible to address those liabilities?
2. Systems	
Next, consider interventions that will facilitate resilient systems that support diverse species composition and structure, sustain biological processes, and provide sources of renewal.	
Existing resilience?	How resilient is the system now? What threats currently limit system resilience?
New and exacerbated stressors from climate change?	Will climate change add new stress to the system? Will new stressors compound existing threats?
Climate effects on processes?	How will climate change effect processes like disturbance and regeneration? What is the system's anticipated response time to climate change?
Existing ecosystem services?	What ecosystem services (e.g., flood water storage) does the system provide? Can these services be enhanced?
Response feasibility?	Can threats or stressors be feasibly managed at the site level or is another approach needed?
3. Species	
Diversity is a key component of system and site resilience. Although land managers have a tremendous array of options to manage species at sites, not all will advance the site's long-term climate resilience. Therefore, species-level interventions should be carefully selected and embedded within a management process guided by the Core Principles of Managing for Resilience (Section 2).	
Edge-of-range species?	Are there edge-of-range species at the site that may become more or less abundant as climate change shifts their distribution?
Vulnerable species?	Are there certain species that are especially vulnerable to declining vigor in a changing climate? Do these vulnerable species have an outsized impact on the structure and function of the site (e.g., keystone species)?
New species?	What species could be established at the site as regional climate changes? Are any of these potential new arrivals likely to be detrimental to site or system resilience? Do any of the new arrivals have functional traits similar to vulnerable species already present at the site? Do any of the new arrivals have functional traits not held by any species present at the site?

Species transition consequences?	What are the consequences of species transition at the site? Can they be minimized? For how long?
Species with socio-ecological value?	Are there vulnerable species with important socio-ecological value at the site?
4. Site in a landscape context	
Understanding the desired function of a given site at the landscape scale is essential for determining what changes are acceptable or unacceptable. This lens can give priority to certain interventions based on the valued and unique characteristics of the site.	
Resilient and connected landscape contribution?	How does the site contribute to a resilient and connected landscape?
Most important conservation values?	What conservation values are especially important at the site (representation? connectivity? rare, threatened, or endangered species?)
Protection context?	To what extent are the species and natural communities present at the site protected elsewhere across their range?
Comparable sites?	To what extent are the species and natural communities present at the site protected elsewhere across their range? How are similar sites being managed elsewhere in their range? Should the site be managed similarly or should we adopt a different strategy to spread risk across the landscape?
Programmatic and strategic values?	Are there programmatic or strategic values at the site that should influence management design and implementation?
5. Social and cultural considerations	
While these questions are listed last, the connection, relationship, and benefits to people and communities should always be considered at every step of land management.	
Benefits to people?	Are there actions, existing or possible, that can enhance the ecological resilience of a site while providing benefits to people? Do people value the benefits provided by an action?
Impacts on people?	What are the impacts of a proposed action on people? What are the impacts of inaction on people?
Impacts from people?	Are there existing socio-ecological interactions that degrade the resilience of a site? Are people aware of the consequences of that interaction?
Science, communication, and policy goals?	What is interaction between our science, policy and communications agenda at the site?
Diversity, equity, inclusion, and justice considerations?	Are there members of marginalized communities that have relationships to the site? Does the site interact with any climate impacts that have a disproportionate effect on vulnerable people nearby or downstream?
Tribal Nations and Traditional Ecological Knowledge?	Are there opportunities to engage indigenous communities? Can Traditional Ecological Knowledge inform approaches? Are there species, uses, or characteristics of the site that are especially important to indigenous peoples?

Many of these questions will be difficult to answer for land managers. In some cases, the data may simply not exist or may not have the resolution or certainty desired by land managers. That said, many of the lands managed by TNC have a long history of ecological inventory and management that could provide valuable site-level data. A review of the available data and management history is an essential part of this process—both to inform future management and to identify future monitoring needs.

Managers may find it helpful to refer to these appendices for more information and resources about data sources, vulnerability assessments, and climate projections:

APPENDIX A: Climate Change Vulnerability Assessment Frameworks and Resources
This appendix provides summaries and links to several resources, as well as a short discussion with additional questions and guidance on understanding climate change effects on seasonality and sites over long timescales.

APPENDIX B: Evaluating Climate Change Vulnerability Assessments
This appendix provides a discussion of different types of vulnerability assessments and their relative strengths, weaknesses, and usages.

Section 4.2: Select a Management Approach

The site assessment in the previous step, along with the site prioritization and other actions covered in Section 3, should prepare the land manager to select a high-level management approach for the site. The options include "Monitor for unacceptable change," "Manage to resist change," and "Manage for resilience and allow biota on site to transition."

Table 4.2: Overview of the Managing for Climate Resilience approaches

Approach	Description	When to use
1. Monitor for unacceptable change	This approach calls for no immediate action to manage changes at the site. Managers should periodically revisit this decision, ideally through monitoring. It should be selected with the same rigor and evidence base as strategies that employ active interventions. Monitoring effort must be informed by the site, capacity, and cost of allocating resources and funding.	• Sites with relatively low vulnerability and exposure to climate change • Vulnerable sites or sites with existing stressors that are beyond effective control • As 'control' for network of similar sites that are actively managed

		• When changes are ecologically/socially acceptable
2. Manage to resist change	Short-term emergency approach to sustain critical biodiversity unlikely to persist in a changing climate. This approach is best considered to be time-bound and as the first stage of a long-term management approach to enhance resilience or transition to a new suite of species and or processes.	• Vulnerable sites with very high biological or cultural value • Sites where societal expectations may shift, creating enabling conditions for eventual transition to resilience management
3. Manage for resilience	A set of actions intended to maintain diverse, productive ecosystems, allowing species to move, adapt, or persist depending upon their individual responses to gradual, but continuous changes in ambient conditions as well as increased extreme disturbance events associated with climate change. See Section 5 for additional context and examples.	• Sites with relatively high vulnerability and exposure to climate change • Sites with intact geophysical conditions and abundant microsites

Comparing "Resistance, Resilience, Response/Transition" definitions and frameworks
This subsection provides context about these concepts by exploring their relationship to other widely used climate adaptation decision frameworks to assist managers in selecting the appropriate strategy for a site or system. We also believe that this is helpful in further understanding what actions, approaches, and principles fall within the 'manage for resilience' approach.

The "Resistance, Resilience, Response/Transition" decision framework proposed by Millar et al. (2007) for forested ecosystems is now widely used among forest climate adaptation-based networks, such as the US Forest Service's (USFS) Northern Institute of Applied Climate Science's (NIACS) Climate Change Response Framework (CCRF) and the Adaptive Silviculture for Climate Change project (Nagel et al. 2017). Choosing to manage ecosystems with a "Resistance, Resilience, Response/Transition" framework addresses potential natural or human manipulated changes in the ecosystem that either "forestall impacts and protect highly valued resources" (resistance), "improve the capacity of ecosystems to return to desired conditions after disturbance" (resilience), or "facilitate transition of ecosystems from current to new conditions" (response/transition). This framework works best when addressing pulse disturbances in ecosystems, such as fire-adapted ecosystems, but can be less helpful when addressing gradual and continuous change in ambient conditions. Resilience and transition strategies will be most appropriate when considering a system's climate vulnerabilities due to gradual change.

Table 4.3: Comparison of terms for management actions between the widely used resistance/resilience/ transition framework proposed by Millar et al, 2007 and terminology employed by The Nature Conservancy.

Climate adaptation-based network term	Issue addressed	Example	TNC term	Explanation
Resistance	Critical biodiversity unlikely to persist under changing climate	If the species populations or ecosystem are out of sync with the climatic template, such as mesic tree species in a drier climate, then it is likely to require significant resources to sustain the target at the site	*Resistance* (Manage to resist change)	This is a short-term emergency strategy. Nature moves and adapts to changes in climate. Resisting this goes against natural processes and should be considered only in emergencies until a long-term strategy is found.
Resilience	Recovery from extreme climate events	For example, avoiding timber activities in resilient forests (passive) or releasing seed trees that are maintaining resilience (active) would be a favorable choice when resistance or transition creates more risk to the health of the forest ecosystem	*Resilience* (Manage for resilience)	TNC merges Resilience and Transition because the sudden availability of space and resources resulting from extreme events often leads to transition, and changes in the ambient temperature and moisture make it unlikely that systems will return to exactly what they were before. To maintain diverse and productive ecosystems, our aim is to manage these messy transitions so species can persist, move, or adapt depending on their individual responses.
Transition	Adaption to inexorable change in ambient temperature and moisture regimes	For example, in geographies projected to have hotter and drier future climates, managers may choose to manage for a shift to a greater abundance of fire adapted species in the landscape		

The resilience and transition strategies in Millar's framework are complementary to and overlap with the climate resilience approach presented in this document. TNC's terminology merges the concepts of resilience and transition (see Table 4.3) because the sudden availability of space and resources resulting from extreme events often leads to transition, and changes in the ambient temperature and moisture make it unlikely that systems will return to exactly what they were before. To maintain diverse and productive ecosystems, our aim is to manage these messy transitions so species can persist, move, or adapt. Managing for resilient systems addresses potential natural or human manipulated changes in species composition and structure of ecosystems, which is complimentary to, and often dependent upon, having a resilient site. Our aim is to sustain resilient systems in perpetuity by fostering their inherent resilience characteristics and managing change.

It is also important to recognize that in some instances taking no active management actions (i.e., monitor for unacceptable change) is the most appropriate management decision for maintaining and enhancing resilience. There are instances where the extent or severity of any given stressor is beyond the point of effective control, or engaging in management could cause more harm than good. In other instances, resources may not be available to complete the management project and/or achieve the desired change. The decision to take no action should be made with the same rigor and supporting evidence as any active management strategy. The decision should include if and how to monitor the site for undesirable change with a timeline for revisiting the decision to suspend active management.

Although we cannot resist the changes in climate and ecosystems, there may be rare scenarios in which devoting resources to saving a species or system, or a system process (e.g., disturbance regime of fire-adapted forests that will no longer continue to burn naturally) for a period of time is merited given its value or sensitivity to the landscape as a whole, or for the potential future benefits of refugia. Active resistance strategies may also be favorable for representative sites until societal or stakeholder acceptance creates the enabling conditions for managers to enhance site resilience or aid in the transition of an ecosystem to a new suite of species or disturbance regimes.

Appendix C contains additional information and context for these approaches, a discussion of how they relate to other widely used climate adaptation frameworks, and an overview of specific management approaches that are considered within managing for resilience.

Section 4.3: Design Management for the Site

After selecting the overarching management strategy, the next step is to design management of the site. It is important to implement actions that make the site the most resilient to climate change given the best data and resources available. In many cases, the available data may fall short of providing the certainty and clarity about specific actions. In these cases, the core principles of managing for resilience (outlined in Section 2) will provide an important handrail for designing appropriate management actions. This also underscores the importance of monitoring and evaluation to inform future actions at the site and inform conservation practices more broadly.

The management planning process will be familiar to most TNC land managers who routinely define targets, goals, and objectives and prioritize actions. The new dimension is incorporating the values of terrestrial resilience. We believe the high-level goals and core principles outlined in the previous section will be essential companions to land managers as they navigate this process.

Section 5 of this document will provide additional tools, resources, and context for working through this section of the management cycle. It is important to note that:

a) The land manager has a deep understanding of site condition and historic ecosystem dynamics and therefore is well positioned to lead the management design process, but should seek input from other TNC staff, partners, outside experts, and stakeholders as appropriate.

b) We do not have the capacity to implement actions everywhere, and we must accept that reality.

c) Long-term objectives may be less clearly defined in an era of rapidly changing climate, and managers may wish to identify more clearly defined short-term benchmarks of success.

d) Monitoring should be scaled appropriate to the resources available, magnitude and types of change anticipated, and be specifically designed to inform management.

e) Managers may need to consider where there are management actions that may need to stop to focus actions at high priority sites.

f) Restoration strategies are varied and may need to be applied at a scale larger than the site to address the sources or root causes of degradation. Preventing nutrient and sediment inputs to an estuary, restoring natural river processes like flooding to a highly regulated floodplain, or reintroducing fire to a fire-suppressed landscape may require another approach entirely, perhaps working in coordination with TNC's science or policy teams. In these cases, we encourage land managers to consider how the site, or management of the site, can be used to provide additional leverage to a larger strategic objective.

Section 4.4: Do, Learn, and Share

The final step in the adaptive management cycle is project implementation and learning/sharing. Incorporating climate change into our management planning is new for many of us so this final stage is a critical part of the cycle if we are to learn and adapt our strategies over time in response to changes. We need to know if change is occurring (i.e., choosing the management strategy of "Monitor for unacceptable change") as well as if the management strategy we have selected is working. Designing relevant monitoring is important. Documentation of actions is integral to our learning, and sharing it with others is critical when climate change impacts are becoming increasingly more apparent. Your documentation could inform future adaptation strategies.

Doing (Implement strategy and monitoring)

Implementation includes project management skills with familiar practices such as developing a workplan, creating a budget, obtaining adequate funding and other resources, and engaging stakeholders. Additionally, in order to know if we are successful in our implementation we need to monitor. Best practices include developing methods before a project starts and figuring how to cost effectively implement monitoring over the relevant time frame. The goal of monitoring should be to identify only what we need to know to assess the status of targets in relation to management actions and the effectiveness of selected management strategy over time. Ideally, indicators or key ecological attributes to monitor should be based on project objectives, few in number, and easily measured and interpreted, particularly over long time periods. Monitoring may also be the collection of qualitative data and does not need to include time consuming and complex data collection and analysis. Methods and results should be archived appropriately so they are available to future managers.

Learning and Sharing

Learning from our management actions and sharing what we know is critical to increasing the pace of climate relevant management actions. Evaluation of strategy effectiveness should be built into project reviews to allow managers to refine or alter existing strategies or identify new ones.

Given the complexity of management, it is increasingly important that you share what you have learned with relevant audiences, especially TNC's communities of practice – e.g., stewardship (stewardship@tnc.org) and invasive species (invasives@tnc.org) listservs.

As part of setting up this guidance, the TNC North American Region's Center for Resilient Science has created a document library on their Connect site specifically for capturing Managing for Resilience Case Studies. We encourage managers to post case studies. We are looking for case studies that range from management plans where climate resilience strategies have been included, to monitoring approaches and results, to completed projects where climate resilience strategies have been implemented and there are lessons to be shared (e.g., results of evaluation). Case studies do not need to be robust full documents, but can be as simple as name and a short summary describing the project/effort. Instructions for adding or uploading documents are included at the Connect site. We have chosen Connect so that we can build a searchable library for current and future land managers.

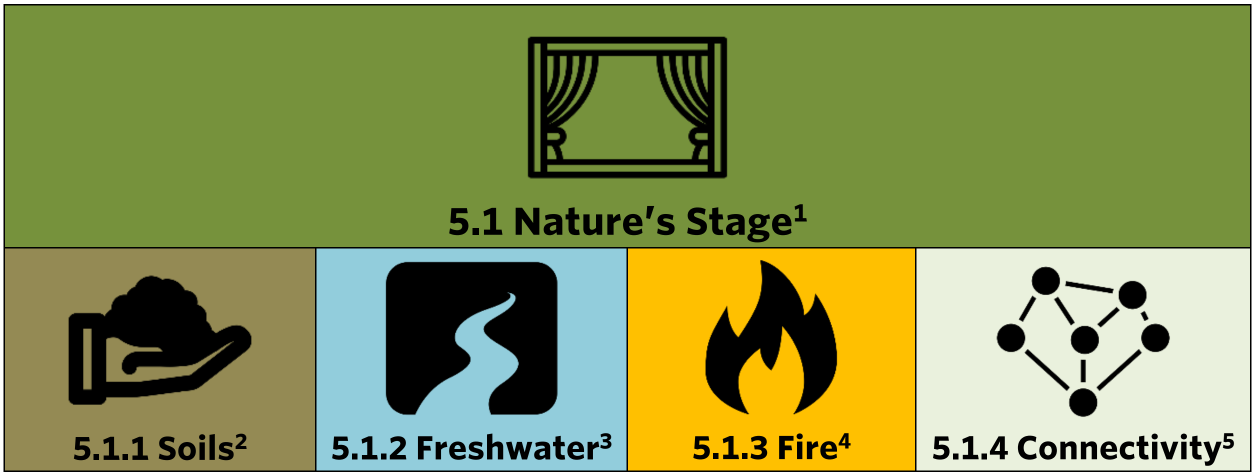
As mentioned in the introduction, we regard this guidance as a living document and the start of a larger conversation among managers about how we adapt our management strategies to the new reality of climate change.

5) Design Management for Site

This section provides land managers answers to questions for each subsection; it is not meant to be read from start to finish. Instead, we encourage you to review the information in the subsection relevant to your site. Each subsection provides answers to these questions about the title topic:

1) Why is this topic an important management consideration for building site resilience in terms of biodiversity, productivity and/or ecosystem function?
2) What are expected climate change impacts on this topic?
3) What are potential methods to enhance site resilience through management of this topic?
4) What should we be looking for when we monitor to know if resilience is enhanced? What are useful thresholds to apply? What is useful in terms of monitoring?

Many subsections also include additional resources for managers who are seeking primary sources, research, and tools to support their work on that topic.



[1] Stage icon by nareerat jaikaew from the Noun Project
[2] Soil icon by Ben Davis from the Noun Project
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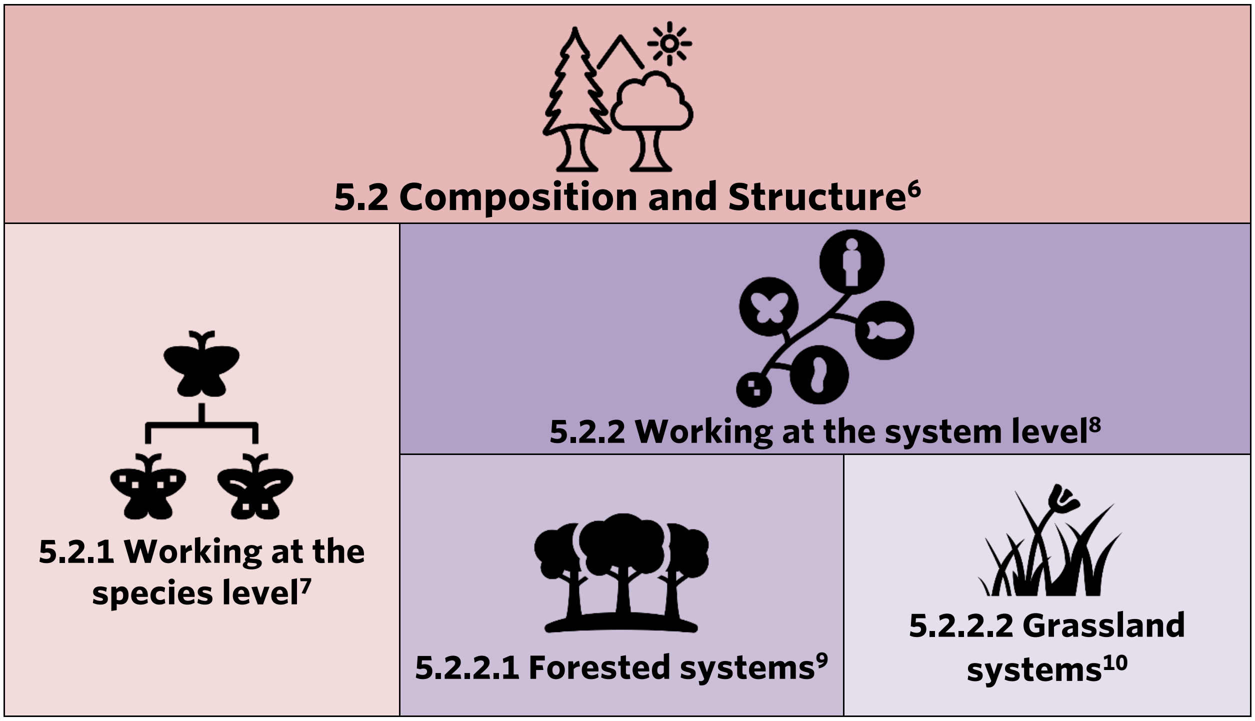

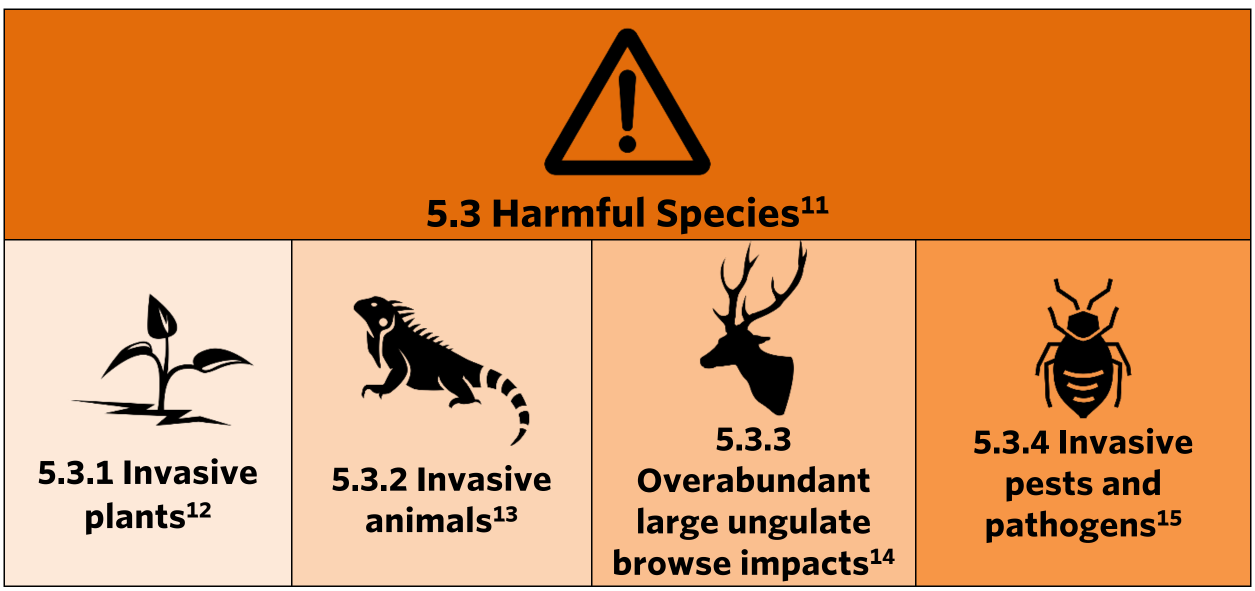

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5.1 Nature's Stage

A resilient site is a defined geographic area that, because of its geophysical structure, continues to support diversity, productivity, and ecological function even as the biota changes in response to climatic change. The characteristics that create site resilience include topographic and hydrologic diversity that create climatic options for species by providing many local microclimates and connectedness that allows species to move to suitable habitat without leaving the site. Identifying resilient sites has been the focus of TNC's terrestrial resilience mapping for the last decade, and maps of site resilience now exist for the conterminous US. In TNC's analysis, resilience characteristics are defined relative to a specific soil, geology and ecoregion to ensure that the full spectrum of diversity is represented.

The TNC resilience analysis allows managers to easily assess a site's resilience characteristics, but ground survey is necessary to evaluate the condition of the geophysical stage and determine appropriate management actions to sustain or restore the characteristics that build resilience. Fragmented connections, degraded soils, poor water quality, and disrupted processes can all compromise a site's resilience.

> ***Given the fundamental role that these geophysical properties play in sustaining current and future biodiversity, we encourage land managers to consider restoring Nature's Stage as a prerequisite to actions designed to foster resilient systems. At individual sites, management of Nature's Stage should prioritize actions that address vulnerabilities and threats identified in the planning process (Section 4.1).***

In this section, we give examples of practices and strategies aimed at improving site resilience characteristics which are the foundation of supporting resilient systems. This list is not comprehensive, but focuses on key elements that are common across many sites. Additional examples can be found in Appendix C.

5.1.1 Soils

Why are soils an important management consideration for building site resilience in terms of biodiversity, productivity and/or ecosystem function?

Generally, soil resilience will be increased by increasing resilience of vegetation, because the two systems are highly linked. Direct manipulation of soil physical properties is not likely a practical management approach for increasing forest resilience, but reintroducing key organisms from the native microbiome -in particular mycorrhizal fungi - may be a helpful condition for restoration. Evidence from grasslands suggests that reintroduction of plants without the reestablishment of native plant microbiomes may be limiting restoration success (Policelli et al. 2020; Koziol et al., 2018).

Soils are ecosystems that can be managed for their own diversity, resilience, and function. Soils are also contributors to and constraints on the functioning of other systems, like vegetation and aquatic systems. How soils can be managed to build resilience depends, in part, on whether conservation objectives target soil as an end in itself, or as a tool for management of other systems.

Though there are strong advocates for conservation of soil as an end in itself—the Global Soil Biodiversity Initiative focuses on soil biology, while Conserving Nature's Stage focuses more broadly on conserving geodiversity—most conservation organizations treat soil as an intermediary to other conservation objectives. Some examples of soil as a tool include:

- Soil management that increases organic matter and aggregate stability that can increase water infiltration and retention to help systems buffer against drought. This is most relevant for arid and semi-arid systems.
- Soil fungal networks have been shown to be important to the exchange of nutrients and water between soil and plants and among plants.
- Soil management can lower loss of sediment and nutrients to aquatic ecosystems, enhancing biodiversity of those systems.

- Soil management may be necessary when restoring degraded agricultural or industrial lands and allow for more direct manipulations than when working in the context of natural lands.

How to manage soil as a tool for resilience is complicated because many soil properties are too difficult or expensive to manage directly, and instead are most effectively managed through impacts on vegetation.

To build soil organic matter directly, a high number of organic inputs have to be added to soil, like compost. This can be expensive. Building additional organic matter can be most challenging in forested systems where vegetation and soil are strongly coupled, and any additional carbon to the soil comes because of increased carbon from vegetation. Because additional carbon comes from vegetation, maximizing soil carbon may require large shifts in vegetation type, which could be undesirable for other conservation and restoration objectives. Building additional carbon is less challenging in row crop and grazing systems where tweaks can be made to crop and livestock management—like cover crop use and stocking density management—that increase carbon inputs to soil. In cropping systems, many efforts to build organic matter focus on indirect management, by manipulating vegetation with practices such as cover cropping, crop rotation, and reducing soil disturbance.

In non-cropping systems, adding organic matter can lead to undesirable trade-offs, like increasing nitrous oxide emissions, lowering water quality, and lowering biodiversity, mainly because of additional amounts of nitrogen and phosphorus that come with greater organic matter (Gravuer, Gennet, & Throop 2019).

Some soil properties are impossible to directly manage. For instance, soil texture is a fixed property of soil and cannot be changed. Relatedly, soil microbial communities are so complex and so quickly change in response to abiotic and biotic soil conditions that directly and permanently impacting the whole soil microbial community is essentially impossible. It may be possible to create conditions for healthy microbial communities and networks through partial retention of legacy trees and protection of refuge plants, as well as preservation of the forest floor (Simard et al. 2020). More targeted inoculation of soil microbes in plant roots, however, is possible and there is some evidence that this can help with restoration by promoting individual plant health, though the science lags far behind public interest.

In north temperate regions of the U.S., non-native European earthworms have invaded the soil in many locations substantially changing hardwood forests. Impacts include consumption of organic layers, altered nutrient dynamics, and altered soil horizons. These changes can impact the cover and diversity of herbaceous plants and tree seedlings (Frelich et al. 2006; Hale et al. 2006; Holdsworth et al. 2007). Evaluation of earthworm presence can be important for determining possible trajectories for forest communities.

What are expected climate change impacts on soil?

Soils, like all ecosystems, are intricately linked to climate change. Soil nutrient cycling is particularly sensitive to climate and weather because these processes are carried out by living organisms that are temperature sensitive. Microorganisms in the soil carry out many soil nutrient cycling processes; when temperature increases, these organisms become more active and carry out nutrient cycling at a faster rate.

For some soil processes—mainly the cycling of carbon and nitrogen—microbial processes can contribute to climate change. As temperature warms, microbial respiration of carbon to the atmosphere increases, potentially leading to additional carbon loss. There have been many efforts to synthesize experimental data on soil warming. The most recent syntheses suggest that soils will lose more carbon as temperature increases, especially where soil carbon is currently protected as permafrost (Crowther et al. 2016). In wet tropical forests, microbial respiration will not change the carbon balance because most carbon is in trees. But in high-latitude places, much of the terrestrial carbon is in soil, and thawing and increased heterotrophic respiration will lead to an important loss of terrestrial carbon to the atmosphere. Feedback between microbes, soils, and climate are not fully represented in global climate models, although we know this process occurs from empirical data. The relationship between warming and microbial respiration is highly complex and depends on a myriad of other soil properties like moisture/aridity, microbial community composition, soil aeration, nutrient status, etc. It is therefore difficult to make accurate predictions of how soils will respond to climate change.

What are potential methods to enhance resilience of soils?

Because soils and vegetation are so strongly coupled, management approaches that successfully restore aboveground vegetation will successfully restore and maintain resilience of soil. For floodplain and wetland soils, this also includes management approaches that restore or enhance hydrologic connectivity.

There is some evidence that the process of vegetation restoration can be facilitated by soil management. Some grassland experiments with inoculation of restoration seeds and seedlings with native **microbial inoculants** have led to faster or more effective restoration (Kennedy 2018; Koziol & Bever 2017). However, these results are not universal and depend on the type of plant and the abiotic context (Hoeksema et al. 2010). There is enthusiasm in the agriculture industry about microbial inoculants to improve crop yields, but they are yet to be widely researched to determine their effectiveness (Baas et al. 2016) and may be too expensive to be practical for growers other than of high-value crops. In forests, an intermediate strategy of retaining legacy trees, protecting refuge plants, and preserving the forest floor, can maintain mycorrhizal networks that colonize germinants and improve nutrient supply, essentially creating the conditions that allow for complex mycorrhizal networks to develop (Simard et al. 2021).

Overall, effects of biochar are highly site- and species-specific (Adams et al. 2013). Individual native species might benefit, but there is significant uncertainty about long-term changes to plant community composition as a result of biochar application (Biederman & Harpole 2013) and about the utility of biochar applications in some restoration contexts is debatable (Houghton 2017).

Some of the greatest advances in soil science have given us insight into *why* certain management approaches work and help us prioritize among already existing approaches. For instance, new science about how soil organic matter forms (Lehmann & Kleber 2015) has shown that vegetation restoration that maximizes root production, belowground carbon inputs, and already-processed organic inputs (like compost) will most effectively build soil carbon. Management practices that promote inputs of chemically complex above-ground inputs, like complex leaf litter, does not lead to long-term carbon storage. Conservation management may be constrained by the vegetation that can be promoted because the conservation goals revolve around specific vegetation types.

For floodplain, wetland, and riparian soils, there is considerable overlap between freshwater management and soil health. Maintaining or restoring critical hydrogeomorphic processes, such as floodplain inundation, sediment deposition, and seasonal saturation, are direct ways to influence soil properties and build resilience at a site. They are covered in greater detail in the freshwater section.

What should we be looking for when we monitor to know if resilience is enhanced? What are useful thresholds to apply, what is useful in terms of monitoring?

Generally, the best proxy for determining the resilience of soil is to assess the resilience and health of above-ground ecosystems.

Soil food webs are a good indicator of soil resilience. For instance, are fungal types that associate with native plants abundant? However, this is challenging given the lab costs associated with genomic analysis.

5.1.2 Freshwater

While this guidance document is focused on terrestrial resilience, there is an undeniable link between freshwater and terrestrial systems. Many of our preserves include freshwater systems that can be managed to improve both terrestrial and freshwater resilience. Land managers may want to consult with freshwater experts in determining the best course of action for maintaining and monitoring hydrologic systems on TNC preserves.

Why is freshwater an important management consideration for building site resilience in terms of biodiversity, productivity and/or ecosystem function?

Freshwater and terrestrial systems are intrinsically linked. For example, forested watersheds reduce storm runoff, stabilize streambanks, shade surface water, cycle nutrients, and filter pollutants. In forested floodplains severely incised streams that no longer have access to the floodplain undermine the long-term resilience of the site and surrounding landscape. Without prolonged periods of inundation and routine influx of sediment and nutrients, the site will be regulated to a greater degree by upland forest processes and may experience a transition in composition, structure, or function. The impacts of transition may have larger implications for landscape resilience, as floodplain and riparian habitats provide important resources for wildlife, may present distinct micro-climates from the surrounding landscape, and are linear features, making them important conduits for wildlife dispersal.

Freshwater restoration may be among the most widespread opportunities for TNC land managers to improve the geophysical condition of sites under their care. In the Northeast, for example, a history of deforestation, cultivation, abandonment, and reforestation has left far reaching damages to freshwater systems. In Vermont, 75% of river miles assessed by the Department of Environmental Conservation are incised and disconnected from their adjacent floodplains. More than 70% of the state's river miles are small first- and second-order streams, a size commonly found on TNC managed lands. On these smaller streams, land managers have the opportunity to deploy low-cost, low-tech solutions to restore critical stream and floodplain processes.

Freshwater systems face a global threat and precipitous biodiversity crisis, and many of the freshwater management actions land managers might use to improve terrestrial resilience are justifiable from the aquatic benefits alone. While the footprint of management on TNC lands might be small compared to the scale of the problem, the demonstration value of implementing progressive water quality projects on TNC lands may have high strategic return.

Lastly, management of freshwater provides direct benefits to people, such as clean drinking water and reduced flooding, that warrant consideration in their own right. That these benefits are easily understood and communicated is an advantage for managers trying to engage audiences and communities about management actions on TNC lands.

What are expected climate change impacts on freshwater?

While specific climate change impacts may vary depending on location, the Eastern U.S. is expected to have a range of temperature and precipitation impacts from climate change by the end of the current century that will impact our freshwater ecosystems. Precipitation changes are expected to impact snow cover, spring snow melt, peak stream flow, aquifer recharge, and water quality. These changes are likely to alter hydrologic regimes including timing and severity of high and low flows as well as water temperature increases. Changes due to winter warming and the timing of spring melting are expected to reduce groundwater reserves during subsequent seasons. For example, vernal pools, which are important breeding and foraging habitat for many species, could be affected as they rely on abundant spring snow melt to be filled. If summer precipitation decreases, wetlands may become isolated, causing loss of habitat for aquatic organisms, loss of aquatic connectivity, and the consequent restriction of movement between wetland systems. Weaker spring floods could alter systems such as floodplain forests that depend on seasonal floods and alter nutrient and sediment regimes (Grubin et al. 2007).

It is worth considering that the impacts of climate change will be overlain on freshwater networks that, in general, are radically altered, diminished in habitat value, and function as a source, rather than a sink for nutrients and sediments, increased flood flows, and risks to downstream communities. Many of these networks are unstable and degraded in a manner that does not yield positive change. In areas with expected increased precipitation and more frequent and severe storms, these unstable systems are likely to continue to degrade.

What are potential methods to enhance site resilience through management of freshwater?

Resilience is the ability of a stream network or other aquatic system to maintain native diversity even as the system changes in composition and structure in response to changes in climate. Our assumption is that the physical factors listed in the table below (long, connected stream networks that allow populations to move, and that contain enough options) will better facilitate changes in aquatic species composition and structure in response to physical changes directly driven by climate change (e.g., average annual water temperature, annual high and low flow rates, etc.). Additionally, systems with intact key processes will be better able to adjust to new ambient conditions, such as waterways with unaltered hydrology or unimpaired interactions between the stream and its floodplain. Networks with more of these characteristics will be more resilient to climate change than those with less. (Note: ponds and lakes are not addressed here) (Anderson et al. 2019).

Table 5.1.2 Summary table of resilience characteristics of stream networks.

Physical factors of climate resilience	
Setting the stage	Size of connected network
	Size diversity/evenness
Adding complexity	Groundwater contribution
	Temperature/elevation/latitude
	Gradient/confinement (natural)
	Chemistry/Geology/Soils
Condition factors of climate resilience	
Connectivity	1a. Lateral connectivity- floodplain access
	1b. Longitudinal connectivity
Flow	2a. Surface flow integrity
	2b. Groundwater recharge/depletion
Water quality and nutrient load	3a. Catchment intactness and permeability
	3b. Sediment regime alteration

These suggested methods can serve as a jumping-off point for managing for resilience on sites with freshwater features:

1) Use process-based restoration, such as wood addition, beaver dam analogues, or restoration to reconnect streams with floodplains and foster resilience of both terrestrial and freshwater systems.
2) Maintain and restore riparian areas, prioritizing areas where critical freshwater processes are present.
3) Remove or retrofit roads that disrupt freshwater systems to promote aquatic connectivity and minimize incision, channelization, and diversion of surface water. Actions could be prioritized to increase length and complexity of the functional connected stream network. Remove dams and artificial impoundments that disrupt aquatic connectivity or alter thermal dynamics of stream networks.
4) Promote beaver habitat and minimize conflicts with human infrastructure (e.g., beaver baffles for culverts and road crossings).
5) For sites that contain a significant area of freshwater habitats, take a watershed approach to determine the resilience of freshwater ecosystems (see Section 5.2.2.3). Key threats/resilience factors could be outside the boundary of the preserve.
6) Consider additional land protection or work with other partners/stakeholders to protect key aspects of freshwater resilience that may impact the preserve outside its boundaries.
7) Focus on increasing infiltration at the site to help abate flooding downstream and maintain or increase groundwater recharge.
8) Manage for extremes as ranges of variability are changing. This could include management or removal of flow controls so that flow regimes driven by natural rainfall and ground water predominate in the basin.
9) Analyze the physical factors of stream systems listed in Section 6.3 to determine how resilient the system is likely to be and identify areas for restoration.
10) Analyze the condition factors as listed above in Section 6.3 to determine how intact the system is and what could be improved or maintained.

What should we be looking for when we monitor to know if resilience is enhanced? What are useful thresholds to apply? What is useful in terms of monitoring?

These considerations can help land managers evaluate whether management interventions are successful:

- Floodplain connectivity is an important freshwater metric that ties to terrestrial resilience which can be evaluated in the field by channel morphology, vegetation, and other field indicators (e.g., sediment deposition). A number of modeling approaches are available for remote assessment.

- Biologic indicators may be selected for some management actions. In northeastern Vermont, for example, trout biomass responds quickly to in-stream wood additions (Kratzer 2018).
- Longevity of process-based interventions should be considered. Interventions, such wood additions or beaver dam analogs, may have a short lifespan, but should create the enabling conditions for self-adaption and equilibrium at the site.
- Determine the diversity of instream habitats, as measured by channel morphology.
- Analyze the percent impervious surface within the watershed. The proportion of impervious cover or hard substrates (e.g., roads and parking) in a watershed typically increases through urbanization and prevents precipitation from soaking gradually into the ground. Impervious cover can impact streams including hydrological (e.g., runoff and flow), physical (e.g., channel size and shape), water quality (e.g., temperature and pollution), and biological (species assemblages) (MDNR 2012). Stream quality indicators are strongly impacted at 10% impervious cover (CWP 2003); however, recent research has shown many significant declines in numerous stream taxa with as little as 2-3% impervious cover (King and Baker 2010). Strategies could focus on ways to prevent more impervious surface in the watershed beyond the preserve, as well as the promotion of green stormwater infrastructure.
- Water quality metrics, such as temperature and nutrient and sediment loading, may be appropriate for some situations. Given the investment required to gather instructive data from these methods, land managers may be better served by selecting other metrics.

5.1.3 Fire

Why is fire an important management consideration for building site resilience in terms of biodiversity, productivity and/or ecosystem function?

A typical/historic fire regime with a suite of fire-maintained species helps a site withstand or fully recover from disturbance events (i.e., resiliency) by ensuring the site's fire-adapted communities and species are vigorous and capable of regenerating. The loss/change of a fire regime could result in the following events:

- a **loss of biodiversity** (e.g., species directly maintained by fire and those that benefit from fire's indirect effects decline or vanish in the absence of fire disturbance and its attendant effects such as the release of bio-reactive chemicals carried by smoke or volatilized by the heat of the fire). Maintaining the largest amount of biodiversity possible, including fire-adapted species, enhances resiliency by maximizing the pathways of recovery following disturbance (Hutchinson and Sutherland 2000; Phillips et al. 2007; Meyer et al. 2008).

- a **loss of productivity** (e.g., non-fire-adapted species are slower-growing than those in the current fire-adapted system). Note that total productivity is not necessarily maximized in a conservation-fire regime (Martin et al. 2015); biodiversity gains may override productivity gains.

- a **change in the site's ecological function** (e.g., fire suppression leads to less frequent but more intense and potentially stand replacing fires, which kill all woody vegetation on a site and results in the conversion to a shrub or grass-dominated system).

Note that a fire regime consists of intensity, severity, seasonality, and frequency; a shift in just one of these attributes, in either direction, could lead to negative consequences.

What are expected climate change impacts on fire?

In the Central Appalachians and mid-Atlantic, climate change is expected to result in hotter conditions, with greater periods of drought in between precipitation events (Butler et al. 2015; Butler-Leopold et al. 2018). There is moderate agreement that the risk of wildfire could increase by the end of the century, and the behavior of fire during burn events could become more extreme. In a prescribed burn context, the implications are that fire behavior may become more extreme over time; prescriptions may need to be adjusted to adapt to the future climate, and climate change may also reduce the number of days when prescribed fire can be safely conducted. Considerations and planning for new or increased wildfire events including contingency plans, opportunistic monitoring efforts, or the necessity of post-fire restoration.

Additional evidence suggests that fire-adapted ecosystems could benefit from this shift because they are better able to survive and/or thrive after burn events. If forest communities shift in response to climate change, the underlying fire regime facilitated by those species could change as well (e.g., fire-prone oak litter results in more fires). The diversity in these novel fire-maintained communities should be evaluated for their adaptation to fire as they move into more northern settings. Changes in species composition are likely to alter fire regimes especially where invasive species change fuel loading and fire behavior.

What are potential methods to enhance resilience to fire?

Management strategies should address the elements of resilience that are under threat according to three different scenarios:

- To address a loss of biodiversity: Change burn prescriptions to achieve the intensity and frequency needed to sustain fire-adapted species/communities. Keep damaging fire out of non-fire-adapted communities to minimize impacts to species composition.
- To address a loss of productivity: Conduct fuel-reduction burns or treatments to reduce the risk of catastrophic wildfire. Alter prescriptions as needed to avoid undesired fire intensity and severity.
- To address a loss of ecological function: Conduct fuel-reduction burns or treatments to prevent catastrophic wildfire. Alter prescriptions as needed to avoid

undesired fire intensity and severity. Manage invasive species that may alter fuel loading and fire intensity.

What should we be looking for when we monitor to know if resilience is enhanced? What are useful thresholds to apply?

For **site-level assessments**, land managers should:

- Assess whether typical fire behavior in your prescribed burns is changing. Comparing the impacts of past burns vs current burns will help shed light on whether conditions have changed enough to warrant changes in burning tactics.
- Have invasive grasses (e.g., cogon grass, Miscanthus) or other invasive plants changed fuel conditions to the extent that "natural" fire conditions no longer exist on the site?
- Is your ecological target/preserve in a fire-dependent or fire associated system? Is it in a landscape where fire can be safely used as a management option? Are there mechanical options that mimic the effects of fire? Can fire be used in combination with mechanical treatments to achieve desired results?
- What is the long-term capacity for prescribed fire operations at your site? Many priority systems need routine fire exposures making a long-term commitment to implement prescribed fire necessary for the success of restoration and stewardship operations. Is this commitment realistic? Is this commitment shared with partners and the local community?
- What are the likely implications of climate change to your target? To your geography in general? (NIACS Adaptation Workbook; see Appendix C for more context).

For **regional assessments**, land managers should:

- Evaluate whether the occurrence of high-severity wildfires is increasing throughout the region. The extent and severity of wildfires is monitored in most states by a relevant state Agency (e.g., Forestry, Natural Resources). Determine whether immigrating species require similar fire regimes to the current goal. Will these new species alter fire behavior? For eastern USA forests review the Climate Change Atlas.
- Most fire regimes are far outside the historic ("natural") conditions. Do you understand, as best as possible given on-going debates and discovery, the fire history of the landscape/ecoregion, as far back as possible? An example is Omer C. Stewart's 1908 book that attempts to describe historic fire conditions in the U.S.A.

- Are similar fire effects even possible given recent and current land use, and is fire alone enough (e.g., oak-fire hypothesis meta-analysis in eastern US (Brose et al. 2013)?

5.1.4 Connectivity

Why are landscape connectivity and fragmentation important management considerations for building site resilience in terms of biodiversity, productivity and/or ecosystem function?

Maintaining a connected landscape is the most widely cited strategy in the scientific literature for building climate resilience (Heller & Zavaleta 2009). Put simply, species must have the ability to move in response to a changing climate and associated changes in habitat suitability and community composition and structure. Observations of range shifts in response to climate change derived from historic and contemporary evidence point to four primary responses: upslope movement, northward expansions, use of riparian climate corridors, and reliance on microsites for short-distance movements (Anderson et al. 2016).

These four responses lie at the heart of TNC's Resilient and Connected Network, which identifies lands that not only support the short-distance movement of species between microclimates, but are also configured to accommodate landscape level responses of species moving northwards, upwards in elevation, or along riparian climate corridors (Anderson et al. 2016).

While connectivity is fundamental to supporting the rearrangement and dispersal of species in response to climate change, it is also a bedrock principle of ecosystem management that should be familiar to TNC land managers. Connectivity can impact gene flow and thus population viability as well as continuity of ecological processes.

Given the range of ecological interactions that fall under connectivity and the difficulty in measuring the presence or absence of some interactions, it is helpful to distinguish structural connectivity from functional connectivity.

- Structural connectivity is "a measure of habitat permeability based on the physical features and arrangement of habitat patches, disturbances, and other landscape elements presumed to be important for organisms to move through their environment." (Hilty et al. 2019)
- Functional connectivity is "the degree to which the evidence indicates that landscapes or seascapes facilitate or impede the movement of organisms." (Hilty et al. 2019)

What are expected climate change impacts on landscape connectivity and fragmentation?

The primary threat to connectivity is human-driven fragmentation and habitat conversion, meaning the influence of climate change on connectivity will be mediated to a large degree by how our society choose to respond to it. It is possible that climate change will alter the settlement and development pressures (e.g., climate refugees), or that transitions to new forms of energy will trigger infrastructure development (such as ridge-top wind) that present new challenges for connectivity. Climate change will also likely compound other stressors (such as fire, hydrology, and forest pests and pathogens) that could create disturbances or ecosystem transitions that inhibit connectivity.

What are potential methods to enhance resilience through landscape connectivity and fragmentation?

We can manage to enhance structural and functional connectivity at many scales, both within and along the boundaries of our preserves and across landscapes through partnerships. Given the difficulty and specificity required to measure functional connectivity, we recommend that land managers use structural connectivity to design and evaluate management actions. These relevant methods serve as examples:

- Road decommissioning: old roads can impede the movement of many species, impact hydrologic connectivity, etc. Removing roads on our lands can create larger blocks of connected habitat. Evaluate whether roads impede movement up and down slopes, northward or along riparian areas and prioritize those for removal or mitigation.
- Culvert/bridge replacements can improve both hydrologic connectivity for aquatic organisms as well as connectivity for terrestrial species that often travel along riparian corridors. We can do this both on our lands or work with local Agencies of Transportation (AOT) to advocate for culvert replacement on roads adjacent to our lands that would improve movement to/from a preserve.

Advocating to AOTs for right-sized bridges and culverts when they are planning road work can have a significant impact on connectivity.

- Trails should be planned to minimize disturbance and fragmentation within intact natural communities. The New Hampshire Fish & Game Department has created a GIS analysis tool to show the impacts trails can have on wildlife. Similar tools can be useful when planning new trails or evaluating existing trail networks to minimize impacts. Managers may also consider temporary closures of existing trails to minimize disturbance to wildlife during breeding, migration, or other important seasons.

- Maintain/restore suitable natural cover to facilitate movement, particularly in former agricultural or other developed settings (planting hedgerows/riparian buffers). Riparian and other areas that span climatic gradients provide corridors for species movements.

- Climate change may require infrastructure replacements and/or improvements such as larger culverts under roads, rerouting or hardening of trails, and may lead to increased wildfire threats to infrastructure. These adaptations will impact how we manage, how resilient our preserves are in some cases, and how the public experiences our properties.

- Invasive species can degrade otherwise intact, natural ecosystems and serve as a barrier to species movement. Targeting structural linkages (as well as habitat patches they connect) for invasive species management may be as important as creating new ones. Alternatively, in the absence of any structural linkage, invasive species management might enable indigenous species to cross the matrix.

What should we be looking for when we monitor to know if resilience is enhanced? What are useful thresholds to apply?

Land managers should consider these actions for monitoring their sites:

- Evaluate fragmenting features on and around the property that could present opportunities to restore connectivity.

- Measures of permeability (defined as the degree to which surroundings of species are conducive to movement, dispersal, and natural flow of ecological processes) include elements of landscape structure: hardness of barriers, connectedness of natural cover, and arrangement of land uses (Anderson 2016).

- Evaluate connections to areas that will be climate flow zones: northward, upslope, and riparian corridors.
- Wildlife cameras or other passive monitoring approaches and tracking studies can be valuable resources to understand how wildlife move across a given landscape. Monitoring before, during, and after a restoration effort can provide evidence of enhanced connectivity.
- Measures of improved condition (functional connectivity) include reduced invasive plant abundance and cover, native species reestablishment, and effective restoration planting.

Table 5.1.4: Supporting Science and Resources

Name	Summary
Article - Corridor design	Beier, P. 2012. Conceptualizing and Designing Corridors for Climate Change. Ecological Restoration 30:4 pp. 312-319. https://www.researchgate.net/publication/265973565_Conceptualizing_and_Designing_Corridors_for_Climate_Change
Article- Species range shifts	Chen, I.C., Hill, J.K, Ohlemuller, R., Roy, D.B., Thomas, C.D. 2001. Rapid Range Shifts of Species Associated with High Levels of Climate Warming. Science (333): p. 1024-1026.
Article - Habitat fragmentation	Haddad, N.M., Brudvig, L.A., Clobert, J., Davies, K.F., Gonzalez, A., Holt, R.D., Lovejoy, T.E., Sexton, J.O., Austin, M.P., Collins, C.D. and Cook, W.M. 2015. Habitat fragmentation and its lasting impact on Earth's ecosystems. Science advances, 1(2), p.e1500052.
Article - Climate wise connectivity	Keeley, A.T.H., Ackerly, D.D., Cameron, D.R., Heller, N.E., Huber, P.R., Schloss, C.A., Thorne, J.H., Merenlender, A.M. 2018. New concepts, models, and assessments of climate-wise connectivity. Environmental Research Letters, 13, 073002.
Article - Habitat connectivity	Rudnick, D.A. et al. 2012. The Role of Landscape Connectivity in Planning and Implementing Conservation and Restoration Priorities. Ecological Society of America. https://applcc.org/cooperative/our-organization/rudnick-et-al.-2012-the-role-of-landscape-

	connectivity-in-planning-and-implementing-conservation-and-restoration-priorities
Article Tree migration	Woodall, C.W., Oswalt, C.M., Westfall, J.A., Perry, C.H., Nelson, M.D. and Finley, A.O. 2009. An indicator of tree migration in forests of the eastern United States. Forest Ecology and Management, 257(5), pp.1434-1444
Article – Forest fragmentation spatial assessment	Heilman, G.E. Jr., J.R. Strittholt, N.C. Slosser, and D.A. DellaSala. 2002. Forest fragmentation of the conterminous United States: assessing forest intactness through road density and spatial characteristics. BioScience 52(5): 411-422.
Mapping tool - Landscape Fragmentation Tool	Developed by University of Connecticut's Center for Land Use and Education and Research
Mapping tool - Trails for People and Wildlife -	New Hampshire Fish and Game Department's statewide tool to assess existing trails and site new trails in the most wildlife-friendly way
Modeling Tool - graphab	Graphab software is devoted to the modelling of ecological networks from the framework of graph theory
Land Use/Land Cover data sets – National Land Cover Dataset	The National Land Cover Database (NLCD) provides nationwide data on land cover and land cover change at a 30m resolution with a 16-class legend based on a modified Anderson Level II classification system
Land Use/Land Cover data sets – Magnitude of Terrestrial Habitat Fragmentation	Magnitude of habitat fragmentation indicated by largest patch size, by terrestrial ecoregion – at a Global level Also on Databasin - https://databasin.org/datasets/f88b2b0d922642e689864cbd3409c177
Land Use/Land Cover data sets – Forest Fragmentation Classification	The Classification of Forest Fragmentation map layer is a grid map of North America, including the Caribbean and most of Mexico, showing the amount of forest and the connectivity between patches of forest.

5.2 Composition and Structure

Working in places with high site resilience and restoring the condition of the physical stage creates the enabling condition for biological communities to thrive. However, given the pace of climate change, monitoring and management of the composition and structure of terrestrial ecosystems will also be necessary to enable resilient ecosystems. Our resilient ecosystems goal is to "create a biotic community that exhibits adaptive capacity, flexibility, and stability to sustain its diversity, function, and services despite exposure to disturbance and climate change" (See 2. Core Principles). To manage for this goal, we recommend using three strategies proposed by Gunderson (2000) on enhancing resilience of managed systems through adjustments to composition and structure:

1. increasing the buffering capacity of the system,
2. managing for processes at multiple scales, and
3. nurturing sources of renewal.

This three-strategy model is discussed in more detail in Anderson et al. 2016.

- **Options/Buffering**: Increase the components of an ecosystem that buffer it from vulnerabilities by spreading risk and creating redundancies. Examples: Manage for a high diversity of native species including redundant species with similar ecological functions. To aid systems in developing complex community structure with multiple niches, manage for a mixed age-structure with very old individuals as well as young recruits. Ensure that species have access to a range of microclimates.
- **Process:** Sustain the movement of energy and materials facilitated by the biota and which, if disrupted or lost, could lead to degradation. Examples: Ensure soil

development by preventing erosion and nurturing soil microorganisms. Monitor and sustain biotic relationship such as food webs, trophic hierarchies, and pollinator-host plants interactions. Retain water by ensuring the connections between interception, infiltration and flow are not impeded. Evaluate changing fire regimes and how they interact with composition and structure. Monitor keystone species and sustain when appropriate.

- **Sources:** Ensure the supply of biotic material that provide the raw material for new or existing communities. Examples: Manage for thriving source populations with successful reproduction and recruitment. Sustain biological legacies such as seed banks, woody debris and mycorrhizal networks. Monitor connections that allow for immigration and emigration. Take action if the site appears isolated or is losing native species. Keep disturbances to a minimum to give native species a competitive edge over invasive species.

In the next sections, we look at resilience systems from the point of view of ecosystems and individual species. The focus here is on managing key stressors that impact aspects of system resilience (e.g., species diversity, key processes). We address a few priority stressors; however, the process can be applied to others. In many cases, stressors are a legacy of the disruption of some key process (e.g., forest fragmentation, conversion to agriculture, deer overabundance and browse). In other cases, such as for many invasive species, the stressor itself is responsible for the disruption.

5.2.1 Working at the species level

Why is species diversity an important management consideration for building site and system resilience?

Native species missing from or at reduced numbers within a site are expected to impact resilience by altering natural processes and the ability of a system to respond to disturbance, a concept known as the diversity-stability hypothesis (McCann 2000). Another perspective can be found in the keystone species concept, which describes a species on which other species in an ecosystem largely depend, such that if it were removed the ecosystem would change drastically (Paine 1966; Mills et al. 1993). The concept has evolved from predators to include prey, pollinators, seed dispersers, habitat modifiers (e.g., beaver), and hosts (e.g., plant species that provides habitat for numerous other species) (Mills et al. 1993; Power et al. 1996). A well-known example of a keystone species is the wolf in Yellowstone National Park (Ripple & Breschetta 2004; Hallofsky & Ripple 2008) or on Isle Royale in Lake Superior (McClaren & Peterson 1994). The reintroduction of the wolf in Yellowstone impacted ecological factors including stream bank stability, the deposition of organic matter and fine sediment in riparian zones, water temperature regulation via shading, and nutrient cycling (Smith & Bangs 2009). Keystone species declines may be due to natural processes or anthropogenic factors (as summarized in Hale & Kaprowski 2018). It may be the case that the absence or reduction of a species may cause the ecosystem to transform, and, due to their absence, restoration actions that target the historic ecosystem conditions are unlikely to succeed. This is one of many practical reasons that land managers may chose to focus their limited resources for management on keystone species.

Another useful perspective in evaluating diversity and resilience can be found in the concept of functional diversity (Laureto et al. 2015).

There are different types of categories of species introduction that could assist in creating resilience:

- *Augmentation*: adding individuals of a given species to an area where it is already present. (See "Maintain and Enhance Species Diversity" in the pink section of table in Appendix C). This might be appropriate when the genetic variation in an existing population is dangerously low, as was the case with the 1995 introductions of panthers from Texas into south Florida (Johnson et al. 2010). On a smaller scale, the Federally listed plant species, *Agalinis acuta*, has been re-introduced or augmented at several sandplain grassland sites in coastal Massachusetts and in some cases is thriving at the new sites with appropriate management (Lombard pers.comm.).

- *Re-introduction*: bring individuals of a species back to a site where it was known to have occurred but has since been extirpated. This can make sense if the threat/stressors that led to the species extirpation have been identified and abated. This might be done to increase a community's resilience to climate change, particularly over the term of years to decades. (See "Restore Keystone Species" in the blue section of the table in Appendix C). For example, thirty years ago, TNC established its first herd of bison at the Samuel H. Ordway, Jr. Memorial Preserve in South Dakota. The herd has grown to 300 bison and their disturbance has resulted in a more varied grassland that provides diverse habitat for birds and insects. Additionally, beaver re-introduction across North America has been very successful overall, with beavers occupying much of their original range. Beavers have had a profound effect on wetland ecosystems through their foraging and dam building activities (Baker & Hill 2003).

- *Assisted Migration*: bringing individuals of a species to a site beyond its known/historical range. This may be appropriate where: 1) the species range is clearly shrinking/changing (e.g., particularly where the species southern range is contracting and its southern limit is moving northward) and 2) the species apparently cannot disperse to the new site on its own – particularly when this failure is due to anthropogenic fragmentation and disturbance of intervening areas. (See "Introduce species when needed" in the green section of table in Appendix C). For example, several TNC programs have already planted more southern tree species in forest restoration projects in New York and Minnesota (NAICS).

What are expected climate change impacts on species diversity?

Climate change impacts on species diversity are well documented (Millennium Ecosystem Assessment 2005). Climate change impacts will affect species differently and it will be difficult to predict outcomes. We know that climate zones are shifting, there are more extreme weather events, and there are changes in the distribution and seasonal activities of a wide range of species (IUCN 2015). In many cases, species already are much reduced from past levels due to anthropogenic impacts, such as the large declines in insect biomass and bird numbers in parts of the world (Hallman et al. 2017; Rosenberg et al. 2019), or the loss of American elm and American chestnut from introduced forest pests and pathogens. Species decline is expected to continue given existing and new stressors associated with climate change. Key expected impacts to monitor and adaptively manage include:

- The inability of species to migrate in response to climate change could lead to the loss of heat intolerant species.
- Forest pests and pathogens could increase with climate change, leading to a loss of species such as ash from our forests.
- Declines in pollinator insects may lead to reduced seed production in species dependent on specialized pollinators.

What are potential methods to enhance resilience of species diversity?

Re-establishing a species within its historic range or assisting a species in moving north can be a viable approach for enhancing species diversity on larger preserves or when working within partnerships at a regional scale. This approach might not be advisable solely at the scale of a small preserve and might be controversial when considering rare species.

Ideas for site level restoration actions include (see Appendix C):

- Introduce seeds or other genetic material from a southerly section of the historic geographic range.
- Allow and encourage new mixes of native species that are likely to be climate resilient.
- Increase diversity of nursery stock to provide a greater range of species or genotypes.
- Restore pollinators, builders (beavers), filterers (mussels), or carnivores where needed.
- Promote existing populations of specialist species.
- Improve populations of sensitive, at-risk, and displaced species.

- Maintain seed or nursery stock of desired species for use after severe disturbances.
- If site is isolated, introduce native species that are likely to thrive with current site conditions or with changes expected with climate change.
- Introduce native genotypes that may be resistant to expected pests and pathogens.
- Maintain or enhance populations of keystone species if well-adapted to future climate.

What should we be looking for when we monitor to know if resilience is enhanced? What are useful thresholds to apply?

With the augmentation, reintroduction, or assisted migration of species, we should ideally monitor for the ecosystem benefits that we expect to be provided by the addition of that species, rather than just counting individuals. However, this can be challenging, and individual numbers may need to be used as surrogate for ecosystem benefits. Not many studies have measured ecosystem effects of keystone species re-introductions (Hale & Koprowski 2018). See monitoring section on invasive plants below.

5.2.2 Working at the system level

To evaluate ecosystem resilience from the point of ecosystems, keys stressors and ways to address them will be discussed in the following two subsections:

5.2.2.1 Forested systems	**5.2.2.2 Grasslands**

5.2.2.1 Forested systems

Why is forest health an important management consideration for building system resilience in terms the ecological outcomes of diversity, function, and ecosystem services?

Forest health (e.g., low mortality rates, high tree vigor) helps a forested ecosystem withstand or fully recover from disturbance events as overstory trees have been shown to have higher survival rates than saplings and seedlings (e.g., Davidson et al., 1999). Adequate tree regeneration helps a site withstand or fully recover from disturbance events by ensuring that a new generation of forest will develop to replace the old. Forest health is also related to resilience as a site's poor health could result in:

- a **loss of biodiversity** of tree species and associated wildlife (e.g., declining oak canopy trees are killed by drought then replaced by red maple and impacts on mast-dependent wildlife).
- a **change in the site's ecological function and community structure** (e.g., trees are being replaced by shrubs and grass resulting in lower forest carbon sequestration due to poor seedling/sapling stocking).
- a **loss of ecosystem services** (e.g., decline of carbon storage due to productivity losses from climate stressors).

Note that while a slow shift in species composition is likely with climate change, and not necessarily a contributor to lower resilience, the net loss of species or of forest structural and age class diversity could lower resilience.

A site's health isn't static, but is a function of many different variables that change over a forest's lifetime. Because some systems are naturally less productive or have higher baseline mortality, consider site productivity on a <u>relative</u> scale, not an <u>absolute</u> one. The focus should be on whether your current forest is changing away from the baseline or historic norms <u>of that forest type, and whether that matters for climate adaptation or mitigation</u>. For instance, some forest types are defined by their *lack* of a woody understory (e.g., oak woodlands), and even these ecosystems need periodic pulses of tree seedlings to become the future canopy trees. As the climate changes and disturbances potentially become more frequent, adequate regeneration will be key in maintaining forest ecosystem function and biodiversity.

Achieving *desirable* regeneration outcomes can be difficult and unpredictable. Tree establishment and growth are influenced by abiotic environmental factors (such as light, moisture, and soil) and biotic living factors (such as insects, disease, browse, and competition)(Ward et al. 2013). In deciduous forests in the northeast, the density, composition, and size of seedlings and saplings present in the forest before a disturbance event (advanced reproduction) strongly influence regeneration outcomes, although stump sprouting is an important contributor to regeneration for some species like oaks (Wiegel et al. 2017).

In the eastern US, high herbivory, past land use, and invasive plants/competing vegetation are the primary factors that can push natural tree regeneration below adequate levels (McWilliams et al. 2017). In some tropical forests (including South Florida's hardwood hammocks), trees damaged in hurricanes or other disturbances may respond by rapidly producing large numbers of seeds to take advantage of the sites opened up by the disturbance. Additionally, in some pine dominated fire adapted community types, forest recovery is either from trees sprouting or tree species which produce huge seed crops dependent on mineral soil for germination.

What are expected climate change impacts on forest resilience?

The continued health of eastern forests under a changing climate is difficult to predict, as it is an integration of forest pests/pathogens, changing temperature, precipitation, atmospheric composition, and many other factors. Regional climate impact assessments written by NIACS, and informed by numerous subject matter experts, offer informed guesses as to likely outcomes:

- In the Northeast and mid-Atlantic, forest productivity could be higher for several decades due to longer growing seasons and higher temperatures and CO_2 availability. However, increased pest activity, introduction of new pests, and drought could offset or even reverse those gains (Boyd et al. 2013; Janowiak et al. 2018; Butler-Leopold et al. 2018).
- In the central Appalachians, the change in forest productivity is likely to be minimal; other factors such as relatively older tree ages work to dampen the gains noted in other regions (Butler et al. 2015). However, introductions of new pests and pathogens as damaging as emerald ash borer and chestnut blight,

could lead to decreases in forest productivity in this region as well (Boyd et al. 2013).

- Overall, drought stress due to climate change has been identified as one of the top causal agents of future mortality (Clark et al. 2016).
- The most cold-adapted species are likely to decline the most (Butler-Leopold et al. 2018).
- The shift in forest species composition may first be seen in tree seedling populations.
- The shift in forest species is likely to be highly variable.

Even absent climate change, the current demographics of a region's forests may also contribute to changing growth rates, mortality and overall health over the next few decades. For example, in the central Appalachians, 50% of the forest acreage on public lands is in stands over 80 years old (FIA 2019), with homogenous closed canopy structure. In many fire-adapted forests this is towards the upper end of the lifespan for some common species like scarlet oak (*Quercus coccinea*) and black oak (*Q. velutina*), and natural succession and fire suppression is driving these forests to more mesic maple-dominated forests. Even without a changing climate, restoring a mosaic of the full natural range of variation, from early to late successional of the mesic forests of red spruce, northern hardwoods, to the drier fire-adapted forests of oak-hickory and oak-pine forests will be critical to enhancing diversity at the landscape scale.

Evidence of climate change impacts on forest ecosystems is more likely to be seen in the abundance and early growth rates of seedlings than in mature individuals (Fisichelli et al. 2014a, 2014b). Seedlings are more vulnerable than mature trees to changes in temperature, moisture, and other seedbed and early growth requirements. There is moderate evidence and agreement that forest regeneration may face increased risk of moisture deficit and drought during the growing season in the northeast (Fei et al. 2017). Temperature and moisture requirements for seed dormancy and germination are often much more critical than habitat requirements of an adult tree (Kitajima and Fenner 2000). Most eastern tree species occur in very broad temperature ranges but thrive only in relatively narrow moisture ranges, and moisture deficits and drought are more likely to have reduced tree vigor and increased tree mortality, both of which affect forest composition and structure (Clark et al. 2016). Higher temperatures will restrict the *range* of a species more often than they will restrict its *success/density* (Canham and Murphy 2016).

What are potential methods to enhance forest system resilience?

Management should address components of system resilience, such as biodiversity, and ecological function, that provide habitat for wildlife (i.e., food and cover, early and late successional stands for full life cycles) and ecosystem services for humans (i.e., carbon mitigation and water quality). Management that restores and enhances diversity at all scales, from the stand to landscape, is important to forest system resilience. Managing for stand diversity may include advocating for more group selection methods versus even-aged management. At the landscape scale, working with partners will be essential to manage for the full natural range of variation with structural complexity enhancements in early successional to late successional stands. Within 'working forests' TNC can advocate for practices that will limit high-grading resulting in low species diversity and set the trajectory towards greater capacity for regeneration and a targeted suite of species. Ensuring diversity now and into the future will enable forest systems to function for the wildlife that depend on them. NIACS's Adaptation Workbook is an excellent resource for management tactics for forest adaptation strategies and approaches (see Appendix C for more context). Below is a subset that may apply to forest diversity and function:

- Manage herbivory and invasive plant species where needed to protect and promote species and age diversity and regeneration.
- Favor, restore, reintroduce native species, or assist the migration of "nearby native species" that are expected to be better adapted to future conditions (consider new mixes of native species).
- Monitor vegetation recovery following disturbance and consider active restoration if needed.
- Consider expanding boundaries of preserves to increase landform/microsite diversity.
- Promote coarse woody debris to retain soil moisture and microclimates and substrate for regeneration.
- Where there is high herbivory, consider protecting regeneration with woody debris or fencing.

Targeting goals for relevant diversity and ecological functions of forest systems, enhancing patch connectivity for species climate migrations, paired with enhancing the intrinsic adaptive capacity of key species and populations (species level approach), will create buffers for forest climate resilience in an uncertain future.

What should we be looking for when we monitor to know if resilience is enhanced? What are useful thresholds to apply?

Directly monitoring the forest health in a preserve or working forest will help you detect the early signs of change, including the abundance, composition, and growth of tree seedlings, thereby helping you detect the early signs of compositional change and predict how forests will respond to disturbance. The effort should include a site-level assessment and tracking of existing regional, long-term assessments.

For site-level assessments, consider these impacts:

- *Impact of forest health on biodiversity.* Determine whether certain tree species are declining in health and whether the species is regenerating. Presence or absence of understory species and woody regeneration are indicators of site quality. Novel tree species may be an indication of a shift in biodiversity. Forest pests and pathogens may be eliminating formerly dominant tree species.

- *Impact of forest health on ecological function.* Determine whether your preserve is undergoing a state-change. The most common example is forest shifting to shrubland or grassland and impacts from invasive species.

- *Impact of forest health on productivity and ecosystem services.* Examine the growth of select overstory species, as measured by tree-ring width if you have a large enough data set. Pay particular attention to the last 10 years vs the last 50 years. Examine the vigor of select overstory species, as measured by Leaf Area Index or Live Crown Ratio (FIA 2011). Examine the impact of herbivory on seedling growth and abundance (AVID protocol).

For regional assessments, consider these resources:

- *FORWARN II program.* This program monitors changes in vegetation in the continental U.S., using data from the MODIS series of satellites (2000-present). Impacts from disturbances like tornadoes and also overall productivity can be mapped and tracked using vegetation indices like NVDI. With larger preserves (>100's acres), you'll have data specific to the preserve itself, while smaller preserves will be aggregated with surrounding lands.

- *U.S. Forest Service's Forest Inventory and Analysis (FIA) program*. The FIA program has collected data from a national set of permanent plots since the 1940s. Plots have been established at a rate of 1 per several thousand acres, which means that any analysis of the data should be at least at the county or multi-county scale. The FIA database contains data about tree health (crown class, tree grade, % cull). Options for access include:
    - The entire dataset is available for download, but requires some specialized knowledge and training in order to manipulate

  - Online tools allow for custom queries of the dataset.
  - Published reports of FIA data are available, usually at the state level (query "FIA" in the Forest Service's 'Treesearch' database of research publications)
  - Forest Service researchers might perform custom queries of FIA data, if the topic was compelling and/or publishable and some state forest agencies have a forest biometrician who may be willing to help with analyses

- The Forest Service also publishes periodic assessments of forest health (see Potter and Conkling 2017).
- Climate Change Tree Atlas. The U.S. Forest Service's Climate Change Tree Atlas models potential habitat distributions for future General Circulation Model (GCM)scenarios (2100) for 134 tree species. The potential distribution is the habitat that may become suitable for a species to colonize, provided that the GCM predicted climate of the future is accurate and the models capture all relevant attributes pertaining to the current distribution of the species.

While human-induced climate changes are happening much more quickly than past climate changes, the incremental changes in your managed forests may be difficult to observe, making new actions or strategies difficult to justify. Managers are encouraged to think about thresholds for action—what data/observations will you need in order to engage in a new action.

For additional guidance working on National Forests, consider these resources:

- "Toward a Shared Understanding of Climate-Smart Restoration: A Science Review and Synthesis" - To help forest managers and their partners confront this challenge, the first of these reports, published by the National Wildlife Federation in partnership with TNC, reviews and summarizes the science of climate change and forest management and proposes a set of science-based principles for climate-smart forest restoration. These principles lay out a framework for restoring forests with an eye to the future, not just the past. The principles emphasize the need to explicitly consider both climate adaptation and resilience as well as climate mitigation and carbon management in designing and implementing forest restoration initiatives.
- "Restoring Forests for the Future: Profiles in Climate-Smart Restoration on America's National Forests" - The second of these reports, published by American Forests, showcases how those principles for climate-smart restoration are being put into practice by on-the-ground practitioners. By

highlighting and profiling innovative and collaborative restoration efforts from around the country, this report demonstrates that climate-smart restoration not only is possible, but is actually being carried out.

- "A Guide to Advocating for Climate-Smart Restoration in National Forest Plans" - Over the coming decade many National Forests will update their National Forest Plans that will guide forest management for 15 or more years. This document aims to guide public engagement during the Planning process to address climate adaptation and mitigation during this critical period for the planet to act on climate change.

5.2.2.2 Grassland systems

Disclaimer: While this section focused on the grasslands of the Great Plains, many of the concepts apply to grasslands in other regions as well.

Why is grassland health/productivity an important management consideration for building site resilience in terms of biodiversity, productivity and/or ecosystem function?

Biodiversity is arguably the most important factor in grassland resilience and is linked to productivity and ecosystem function. Grassland systems still contain diverse species, vegetation communities, and ecosystems shaped by the regional patterns of climate and soils. Grassland ecosystems have high spatial and temporal variability because of the frequent and often localized occurrence of fire, grazing, and drought (Augustine et al. 2019; Bragg 1995), and biodiversity is key to grassland resilience in response to these processes. Because species are adapted to different conditions and niches, greater biodiversity creates greater productivity and stability because of species complementarity and shifting dominance as conditions change (Weaver 1954; Tilman and Downing 1994; Tilman et al. 2001). There is recent evidence that diversity in grasslands can increase ecosystem resistance to extreme climate events such as drought (Isbell et al. 2015). Maintaining habitat variation is key to sustaining biodiversity (Sieg et al. 1999). Therefore, managing to maintain or improve biodiversity is one of the most important strategies for climate adaptation and resilience in grasslands.

Although biodiversity is a driver of productivity in grassland ecosystems (Tilman et al. 1996), productivity itself is important for both ecosystem and site resilience. Greater plant diversity and productivity better supports other taxa (e.g., floral resources for pollinators, Dorado and Vázquez 2014), and from a site resilience perspective, productivity is important for grassland persistence on the landscape. Much of the remaining grassland in the Great Plains is privately owned (Rashford et al. 2011), and the dominant land use is livestock production. Keeping them productive and profitable is necessary for their survival as rangelands and to maintain landscape resilience through local connectivity.

Finally, maintaining or building ecosystem function (e.g., carbon storage, nutrient cycling, invasion resistance, etc.) is important for grassland climate adaptation and resilience because ecosystem function supports biodiversity and vice versa (Zavaleta et al. 2010). In some contexts, surrounding environmental conditions influence ecosystem function more strongly than diversity (Zirbel et al. 2019), and therefore, managing local and surrounding conditions to enhance ecosystem functions will improve resilience. For example, reconstruction of grassland habitat near existing grassland can increase resilience by improving environmental conditions, reducing invasion pathways, and enhancing biodiversity.

What are expected climate change impacts on grassland health/productivity?

Between 1950 to 2000, the Great Plains had five droughts as severe as the 1930s Dust Bowl (Woodhouse and Brown 2001). The natural climate variability of this region has been exacerbated by a century-long increase in temperatures of more than 2° F (1° C), with increases up to 5.5° F (3° C) in some areas (Joyce et al. 2001; USGCRP 2014). Continued increased frequency and intensity of droughts and storm events is expected. In the Midwest, increased precipitation and warmer winters is leading to more frequent flooding. In some parts of the Great Plains, the number of days with temperatures over 100°F is projected to double by 2050 (USGCRP 2014). Higher temperatures will cause sustained increased water stress and more frequent and extreme drought (USGCRP 2014). Woody encroachment is increasing in many places, and potential state changes have likely happened in parts of the southern Great Plains.

Observed and projected climate trends for the Great Plains include (Walsh et al. 2014; Wuebbles et al. 2014):

- Increased atmospheric CO_2, potentially changing plant growth and competitive interactions,
- Increased land and air temperatures, causing greater soil moisture deficits, including more frequent, long-lasting, and deep drought,
- Longer growing seasons, during which plants use and need more water,
- More rain than snow, adding to water stress because rain tends to recharge deep soil moisture less than snow, and

- Increased intensity of precipitation events, despite uncertainty about change in total annual precipitation.

Observed and projected climate trends for the Midwest include (Wuebbles et al. 2021).

- Increased air and land temperatures, particularly higher overnight low temperatures.
- Increased precipitation, particularly in winter
- Increased evapotranspiration and risk for short-term drought and plant stress
- Increased extreme weather events including hot days (>95°F) and intense storms

Some areas in the Great Plains will experience reduced net primary productivity, changing plant community composition and increased amount of bare soil (Hufkens et al. 2016; Reeves et al. 2017). Climate change and fragmentation may interact to create loss of adaptive capacity at a site (Wagenius et al. 2009). Warmer winters could open gateways for invasive species to move north. Climate change may also impact fire regimes.

Important wildlife species are at risk from changes in these ecosystems. For example, by 2080 burrowing owls are projected to lose 77% of their current range (National Audubon Society 2014 webtool). Grisham et al. (2013) predicted that by 2050, lesser prairie-chicken nest survival will be below the level needed for population persistence.

Prairie species, communities and ecosystems have lower adaptive capacity compared to mountainous landscapes, being relatively flat, low topoclimate variability with little potential for migration especially upslope to more suitable environments (Comer et al. 2018a, Comer et al. 2018b). Sensitivity to climate change may be relatively high in the Great Plains, especially in the eastern portion because of poor landscape conditions including conversion and fragmentation, fire regime departure, and risk of invasive annual grass species (Comer et al. 2018a, Comer et al. 2018b). In addition, projections across the Great Plains suggests increased variability in productivity especially forage production which will increase risks for ranchers and nature-based livelihoods (Briske et al. 2021; Derner et al. 2018).

Management options will probably become more limited in the future as climate changes. Drought stress can degrade native ecosystems (Rondeau et al. 2013) and restrict management options. Shifting prescribed fire windows are one example of these changes (Yurkonis et al. 2019).

What are potential methods to enhance resilience of grassland health/productivity?

The most important way to maintain grassland resilience is to prevent further loss and fragmentation of grassland habitats. Reconstructing prairie habitats to enlarge and reconnect grassland remnants can also rebuild resilience in currently fragmented landscapes. Climate-resilient areas should be the focus of land protection and compatible management efforts as they are natural strongholds that capture substantial existing biodiversity and may correct any bias in current protected lands networks (Anderson et al., 2014). These climate-resilient areas are also more successful restoration locations.

In addition to habitat size and connectivity, grassland resilience relies heavily on species diversity, which itself relies on habitat heterogeneity. Using disturbances such as fire and grazing, prairie managers strive to create a 'shifting mosaic' of habitat patches that provide a broad spectrum of growing conditions for plants and habitat for animals. Periods of disturbance, recovery, and rest each favor different animal and plant species. Landscapes and sites that have a constantly shifting array of those disturbances have the best chance of maintaining their species diversity, and thus their ecosystem resilience.

Although many different tools and techniques can be used to achieve grassland resilience, some specific strategies include:

- Protect remaining grasslands from conversion.
    - Keep private pasture and hayfields productive and profitable to avoid conversion to cropland or other uses.
    - Work with grassland managers on planning that includes adaptive management to weather/climate variability and keeps grassland communities diverse and healthy (see below for more information on this).
    - Increase awareness of the threat of woody encroachment and continue building capacity of land managers to use fire and other strategies to combat that encroachment. Begin discussions about how to manage for resilience if/when irreversible conversion to woody vegetation occurs.
    - Where needed, employ traditional land protection measures such as conservation easements, fee title acquisitions, etc.
- Where feasible, restore habitat to enlarge and reconnect prairie remnants.

  - Use the highest diversity seed mixes possible and work to ensure diversity is maintained through management.
  - Continue experimentation with 'regional admixture' approaches and other strategies to ensure restored prairie communities will adapt to continued climate change.
- Implement and encourage the use of 'shifting mosaic' approaches to prairie management that provide the full spectrum of habitat conditions, including intensive disturbance, recovery, and rest.
  - Help ranchers recognize and value the full spectrum of habitat patch types.
  - Continue developing and demonstrating various approaches that create a shifting habitat mosaic.
  - Ensure that sufficient refugia (from all disturbances) are included in management plans to protect species sensitive to those disturbances. Continue research on the needs of those sensitive species.
- In some cases, active transition strategies such as assisted migration or assisted gene flow for isolated species may be needed, and in cases where grassland has irreversibly transitioned to new ecological states, develop guidance to manage these new systems.
- For globally rare grassland systems (e.g., isolated grasslands in the northeastern U.S.), grasslands will transition to other ecological states without active management such as mowing and fire (e.g., shrubland), particularly during the growing season. Some of these sites are also vulnerable to sea level rise and will need to move inland.

The transition to climate-smart sustainable ranching requires locally tailored and tested adaptation measures (Rojas-Downing et al. 2016). The challenge for Great Plains land managers is to maintain grasslands in ways that will support wildlife resources and sustainable livestock-based businesses. Adaptation is critical to meeting this challenge. Adaptation strategies for livestock production include flexible herd management, changing livestock breeds/types, and geographic relocation (Joyce et al. 2013). This synthesis evaluation of adaptation strategies emphasizes the need for social learning to build capacity in rangelands (Joyce et al. 2013). The alternative to adaptation is the fragmentation of large intact ranches or conversion of native lands to other uses, destroying wildlife habitat, releasing large volumes of soil carbon, and destabilizing ranching communities.

What should we be looking for when we monitor to know if resilience is enhanced? What are useful thresholds to apply?

Identifying and monitoring key indicators of ecosystem state is important to understand how grasslands are changing biologically. For example, prescribed fire is known to prevent woody encroachment in tallgrass prairie, but once woodies have reached a critical threshold, returned or increased prescribed fire alone may not reverse the ecosystem state change (Ratajczak et al. 2016; Miller et al. 2017).

Monitoring for thresholds

- It is important to thoughtfully add monitoring for species, processes, and conditions that are likely to change and/or most impactful for conservation goals. For example, monitoring presence and woody cover may be more useful in identifying grasslands on a trajectory toward a state change than exhaustive plant community analysis.
- Key Ecological Attributes (KEAs):
    - TNC has used KEAs to efficiently and effectively measure progress toward conservation goals for over a decade.
    - Sites may already have a suite of key ecological attributes which have been monitored long-term or at some point in the past. These can be useful framework to continue long-term monitoring that is already aligned with conservation goals and add an additional lens of climate change.
    - Examples of KEAs in grassland systems:
        - Size/extent of the habitat
        - Landscape context
        - Plant community structure/woody canopy cover
        - Population size and demographics of priority threatened and endangered species
        - Species diversity, across multiple taxa when possible
    - The KEA approach can be scaled up regionally and, in some cases, already exists. The benefit is it allows interpretation of long-term and on-going measures for climate resilience.

Monitoring for management effectiveness

- Monitoring management type and frequencies can be coupled with biological KEAs to track whether management is producing the desired resilience pathway for the ecosystem. Examples:
    - Percent landscape burned each year
    - Fire return interval
    - Grazing intensity/return interval
    - Habitat intactness/landscape connectivity
- Grazing and fire are critical ecological drivers for grasslands and regular inclusion of these forces is essential for resilience and to avoid ecosystem state change. KEAs for grazing and fire should include optimal targets (e.g., frequency/intensity). Responses to these management approaches will vary at the local site level, and there is robust scientific literature from many grasslands in North America to help identify these thresholds.

5.3 Harmful Species

The following subsections cover how to address various types of harmful species under changing climate conditions.

 **5.3.1 Invasive Plants**	 **5.3.2 Invasive animals**	 **5.3.3 Overabundant large ungulate browse impacts**	 **5.3.4 Invasive pests and pathogens**

5.3.1 Invasive plants

Why are invasive plants an important management consideration for reducing stress on site resilience in terms of biodiversity, productivity and/or ecosystem function?

Although rarely, if ever, solely responsible for species extinctions, invasive plants are a primary cause of local native biodiversity loss and of ecosystem degradation globally. Through direct competition for resources, rapid growth rates, a lack of co-evolved predators, and prolific seed production, among other traits, invasive plants can quickly outcompete and reduce native species diversity and abundance in terrestrial systems. The resulting impacts to ecosystem productivity and function can vary significantly by species and site. The most significant impacts result from species that drive systemic ecosystem change and where multiple stressors interact producing synergistic effects (e.g., deer over-browse of native vegetation facilitating the spread of browse-resistant invasive herbs and shrubs).

Invasive plants facilitate habitat degradation through direct competition with native plants; disruption of pollination and seed dispersal mutualisms; alteration of ecosystem processes such as nitrogen cycling, alteration of soil composition and chemistry; and displacement of associated specialist and generalist species of wildlife. These impacts can impede the connectivity where structural connectivity alone may not be sufficient to facilitate species movement through the habitat matrix which no longer supports habitat features necessary for any given species' food, shelter, reproduction, or survival. This is especially concerning for specialist wildlife and invertebrate species which are dependent on one-to-several species of native plants.

Invasive plants can also reduce a system's ability to recover from disturbance events by limiting regeneration of native plants, altering or impeding natural disturbance regimes, degrading natural habitat refugia, and moving systems outside of their historical range of variability. The homogenization of an ecosystem's species assemblage driven by invasive plants also reduces species and niche redundancy thereby reducing the capacity of the system to adjust to environmental change, leading to instability and ecosystem transformation.

What are expected climate change impacts on invasive plants?

Climate change will likely make management of invasive plant species more difficult in several ways. First, it will make it more difficult to determine whether plants currently regarded as invasive which spread from lower latitudes and lower elevations should be regarded as invasives subject to control, or populations moving in response to climate change. For example, black locust (*Robinia pseudoacacia*) is now regarded as invasive in sites north of the Potomac River drainage, and as an especially troublesome in protected areas such as the Albany Pine Bush Preserve because it has a nitrogen-fixing symbiont that significantly alters soil nitrogen levels (i.e., it alters a key ecosystem process). Sharry (2018) found that this increase in soil nitrogen may, in turn, lead to increased metabolism of soil carbon and increased rates of CO2 release into the atmosphere. In the coming decades, however, black locust and other species native to more southerly states may begin to migrate northward and to higher elevation sites as the climate warms. Should they be regarded as invasive, or welcomed as climate migrants and new actors on the stages we are protecting?

Second, climate change is likely to favor the establishment and spread of species that could not have arrived without transport by humans or their domesticated animals. As global temperatures continue to rise, invasive plants that have historically been restricted by both annual growing season temperatures and lengths will likely expand their ranges into previously inhospitable areas. For example, invasive plants currently impacting the southeastern United States such as kudzu will likely be able to invade the northeastern states as climate barriers that have heretofore prevented this expansion shift northward. Lengthening of annual growing seasons will provide additional opportunity for invasive plant establishment while extending the amount of time populations are able to monopolize available resources for growth, expansion, and reproduction. Increased levels of atmospheric carbon dioxide will also provide additional carbon fertilization and photosynthetic output to the benefit of invasive plants.

Climate change may also cause some naturalized non-native “sleeper” species that are currently not invasive to become invasive through changing biotic or abiotic conditions. These new conditions could favor their “awakening” and then growth and spread.

The increased prevalence and magnitude of climate change related disturbance (flooding, fire, wind throw, etc.) and the expected increase in severe weather events (droughts, heat waves, severe flooding) that may lead to mass diebacks of native species and vegetation types, will create additional opportunities for invasive plant introduction, establishment, and expansion, and in some instances act synergistically to completely upend natural disturbance regimes (e.g., expansion of invasive grasses into burned areas that then provide ideal fuel for catastrophic wildfires). For example, Japanese knotweed invades areas of disturbance along stream corridors and spreads through fragmentation of root and stem material during flooding events. The propensity of this species to destabilize stream banks exacerbates this spread.

In many wooded areas of the eastern US, white-tailed deer over-browse of native vegetation facilitates the introduction and expansion of invasive understory grasses, herbs, and shrubs which further inhibit forest regeneration. Deer populations in areas currently kept wholly or partially in check by winter mortality (especially from long winters producing deep snow), may boom in mild winters to the benefit of invasive plants. This is especially concerning in areas with compromised overstories due to native or introduced forest pests and pathogens, unsustainable forest management, or competition from already existing invasives.

A last consideration is that climate change may also reduce the efficacy of herbicides. Environmental factors such as CO_2, light, temperature, relative humidity, and soil moisture may differentially affect the uptake, translocation, and activity of different herbicide chemistries. Furthermore, interactions among these environmental factors may have unpredictable effects on herbicide activity.

What are potential methods to make systems more resilient to invasive plants?

Not all invasive plant species or infestations should be or can be effectively managed given limitations on available resources and control methods/technologies. Management may not always result in improved or enhanced resilience of the affected system, especially for invasive plant populations that are beyond the point of effective control or which are symptomatic of other stressors or land-use histories. Adopting a preventative management approach which promotes the maintenance of ecosystem integrity/condition, thereby strengthening resistance to invasion, while facilitating early detection and rapid response to new and/or isolated infestations of high threat species is most likely to foster ecosystem resilience. Limited interventions resulting in lasting change will also help avoid unintended consequences of management actions that may in and of themselves impair resilience (e.g., legacy soil effects from repeat herbicide treatments). Ensuring sufficient native species reestablishment and site restoration, either through active or passive means, will also be increasingly important as any available and/or disturbed space becomes increasingly vulnerable to reinvasion.

Assessing and determining the relative threat/invasiveness of invasive plants affecting any particular TNC preserve or property is the starting point for informed, strategic and science-based preventative management. Focusing on those species/infestations that pose the highest threat, can be effectively controlled, and where likelihood of reintroduction (pathway/vector management) can be significantly reduced or eliminated have the highest likelihood to be successful and provide long-term benefits to ecosystem resilience.

For those invasive plants that are not yet present but could expand their ranges with climate change and eventually colonize and establish, a horizon scanning approach is necessary. Communicating with other invasive plant managers and evaluating invasive plant distributions in areas south of your preserve through invasive plant mapping tools such as iMapInvasives and EddMaps can also provide insight into the species that should remain on your watch list. Maintaining species lists of high threat invasive plants that should be targeted for management and early detection surveys as well as training staff on identification, surveillance, reporting, and best management practices will help ensure a timely, strategic, and effective response to invasive plant stressors.

Once invasive plant management targets have been established and infestations identified, evaluation of the impact on priority conservation assets and the feasibility of control is essential. Evaluation of anticipated costs and return on investment is a critical step in pre-project planning. Ideally, invasive plant management actions should focus on the resilient and connected lands network to improve or maintain functional connectivity, species diversity, micro-habitat refugia, etc. that enhances site resilience. Utilizing TNC's Invasive Plant Management Decision Analysis Tool will help you identify the most appropriate management strategy for any particular invasive plant management project. Priority should be placed on those projects where eradication or containment/exclusion of the invasive plant is likely and where minimal investment will result in lasting or persistent ecosystem benefits. Perpetual or long-term management of this sort is more likely than one-time actions to produce unintended consequences that could unintentionally compromise site resilience (e.g., repeated soil compaction/disturbance and legacy soil effects from repeat herbicide applications). Doing nothing may be the best alternative in many situations, especially for infestations that have expanded beyond the point of effective control or where reintroduction cannot be prevented.

Management of invasive plant infestations alone, even though it may be effective in reducing populations, is unlikely to enhance site resilience. Rather, the reestablishment of native species, natural communities, and ecosystem processes post-management should be the goal and may require active restoration of the previously invaded site. Passive restoration may be appropriate for small infestations (~ $\leq$.1 acres) that have sufficient levels of surrounding native vegetation and seed banking to facilitate native plant reestablishment. However, for larger infestations active restoration will often be necessary in order to ensure adequate and timely native species reestablishment and avoid reinvasion (invasion treadmills) by the same or other invasive plants which quickly capitalize on open space/disturbance.

What should we be looking for when we monitor to know if resilience is enhanced? What are useful thresholds to apply?

In order to ensure that invasive plant management, ecological, and enhanced resilience objectives are met, outcome monitoring is essential to quantify responses to management efforts. For invasive plant management, this requires annual assessments of infestation extent and cover prior to, during, and after treatment. TNC's ESRI Collector-based Invasive Plant Mobile Monitoring System (IPMMS) provides a customizable, easy to use, and efficient data collection and outcome monitoring system for TNC's technical invasive plant managers. In general, invasive plant infestations should not be considered extirpated until after at least three consecutive years of documented plant absence with most infestations requiring at least five years of follow-up monitoring post management. For containment or suppression projects, native plant reestablishment is usually facilitated and able to support pre-invasion ecosystem processes when invasive plant cover is reduced by at least seventy percent. In order to evaluate native species response to invasive plant management activities, native species reestablishment monitoring is necessary. Photo-monitoring is often useful, especially when dramatic recovery of native vegetation is expected/hoped for following the removal of invasive species.

Table 5.3.1. Supporting science and existing planning tools for invasive plants.

Name	Summary
Regional networks that address invasive species and climate change	NE Regional Invasive Species and Climate Change Network - see in particular management challenges
	Pacific Northwest Regional Invasive Species and Climate Change (new)
	Hawaii Working Group
Increasing Forest Resiliency for an Uncertain Future – New England	Framework for addressing challenges to maintaining forest resiliency

Building Resistance and Resilience to Climate Change- Global	A User's manual for building resistance and resilience to climate change in natural systems
TNC's Collector Invasive Plant Mobile Monitoring System (IPMMS)	Connect community for IPMMS
Herbicide Use on Lands Owned or Managed by The Nature Conservancy, Invasive Species Advisory Committee, 2016	Guidance document for TNC herbicide use
Allen, J.M., B.A. Bradley. 2016. Out of the weeds? Reduced plant invasion risk with climate change in the continental United States. Biological Conservation 203: 306-312.	Geographic invasion risk for terrestrial invasive plants under current and future climate scenarios
Zimmerman, C. et al. 2011. An invasive plant management decision analysis tool. TNC, NY	Tool for deciding if invasive plant control project is feasible.

5.3.2 Invasive animals

Why are invasive animals an important management consideration for reducing stress on site resilience in terms of biodiversity, productivity and/or ecosystem function?

This section covers invasive, terrestrial vertebrates, including pigs, snakes, frogs, and birds. Invasive insects and increased herbivory from overabundant native animals are discussed in other sections of this document.

Invasive animals possess the potential to extirpate native populations (e.g., threats to native mammals in the Everglades of Florida [Dorcas et al. 1998]), are a leading cause of species extinctions (especially on islands), and can severely impact the health of protected areas by degrading species diversity and abundance. This damage can be brought about indirectly, by damaging and disturbing soils and native vegetation, which results in an increased abundance and diversity of invasive plants. Invasive animals can also impact human health and have tremendous economic impacts through crop loss, infrastructure damage, and control costs.

Some invasive animals are already well established in their suitable ranges across the US, such as European starlings (*Sturnus vulgaris*), house sparrows (*Passer domesticus*), feral pigs (*Sus scrofa*), or Norway rats (*Rattus norvegicus*), while others are still mostly located at or near their area of introduction. Many examples of the latter occur in Florida and Hawaii due to these locales' tropic or subtropic climate and international seaports. Novel introductions continue to occur through vectors such as intentional pet releases, escapes from exotic hunting camps, escapes from research facilities, escapes from illegal food or pet farming, illegal intentional release of game or fish species, or international commerce.

What are expected climate change impacts on invasive animals?

Similar to invasive plants and insects, trends for warmer weather and milder winters resulting from climate change are expected to facilitate the expansion of many invasive species to more northerly (higher latitude) and higher elevation areas. Changes in climate conditions may also encourage the establishment of populations of invasive animals that would not be successful given historic weather and climate conditions. Combined with the possibility of decreased vigor of native species due to climate change, the threat of invasive animal species to native ecology is increasing. In some cases, climate change may eliminate the southern range of invasive species, due to the new climate exceeding the heat tolerance or other tolerance (i.e., humidity, etc.) of the invader.

In the continental US, Florida has a large number of invasive species (over 500, including plants and insects) that thrive in its tropical and subtropical climate. The green iguana, for example, had been documented in primarily southern Florida's tropical zone following its introduction around 1964, but is now expanding northward. These northern populations have been driven back by occasional, relatively harsh winters, although they have been recovering in subsequent milder winter conditions. If the climate of what are now subtropical portions of Florida come to resemble the tropical southern tip, it is likely that the green iguana will continue to successfully expand northward without intervention. This trend may be similar to many other invasive animals that currently infest southern ranges.

Other animals began spreading successfully long before climate change became a concern to modern land managers. Feral pigs (*Sus scrofa*) were first introduced to North America in the 1500s by European settlers as a food source. Either by escaping their enclosures, or being released intentionally, these animals continue to expand across the continental US. They are the target of a $75 million control effort in the 2018 US Farm Bill due to the damage that they cause to agriculture, ecosystems, and plant and animal health. Impacts of feral pig rooting and wallowing include heavy erosion and root damage to even mature trees. Feral pigs are also a heavy source of predation on ground nesting birds and animals. When combined with climate change, damage by feral pigs may amplify negative outcomes to native ecosystems.

What are potential methods to make the system more resilient to invasive animals?

Educating field staff on how to identify and report odd or out of place animals or animal signs is one way to improve early detection of invasive animals (Mehta et al. 2007). This can be done by having staff attend regular workshops or trainings put on by various conservation organizations, professional groups, or government agencies. Early detection is critical in preventing the establishment of invasive animals, and opportunistic monitoring while performing other duties should become second nature to any staff that spend time on TNC preserves. Knowing what invasive animals exist in the region, or are threatening to enter a region, allows managers to more properly determine the level of monitoring necessary to prevent or reduce the impacts of a given species. Continuing or expanding collaborations with partners, both traditional (government agencies, other NGO's) and non-traditional (citizen science groups, hiking clubs, etc.), to monitor and contain populations is another logical step in combating invasive animals. Strategies to assess and prioritize management actions for invasive plants could similarly be used for invasive animals (see above section on invasive plants). Collaborations outside of the environmental sphere may be possible if a given invasive animal impacts multiple stakeholders in a significant manner.

Managing for the biodiversity and vigor of existing, native ecosystems on TNC preserves is also critically important. This should not be a new goal for TNC land managers, but concerns about invasive animals may provide additional justification for actions that promote native biodiversity and the vigor or native ecosystems, and for increased efforts to secure funding for this work.

What should we be looking for when we monitor to know if resilience is enhanced? What are useful thresholds to apply?

The monitoring principles previously articulated for invasive plants can be applied to invasive animals as well. Constant monitoring of not only current ecosystem conditions, but also the results of management actions, are important to properly inform an adaptive land management strategy. Many of the mapping tools and methodology used to track and treat invasive plants can also be used for invasive animals. Creating monitoring protocols to track presence-absence, or more rigorous sampling for population estimates (e.g., live capture and banding), can be implemented to track the success of control efforts. Animals can also be remotely monitored through the use of game cameras or acoustic sampling and can be actively monitored through the use of traps or direct observations of individuals or signs such as scat and feeding damage.

Opportunistic monitoring for signs of invasive animals should be commonplace for any field staff performing any work on TNC preserves. Having a system in place to document, record, and equally important, query, this data should be a top priority for managers who currently do not have an efficient method for performing these tasks.

Systematic sampling will likely be cost prohibitive without a clear need for the additional cost and employee labor. Passive monitoring, like game cameras, "hair traps" for DNA analysis, or acoustic detectors, can be costly items by themselves. That cost may quickly balloon when the price of batteries, travel to and from the device's location to set and retrieve data, analyze the data, and adequate numbers of the necessary devices to monitor an entire preserve are factored together. Unless a real need for this added cost is evident, it will be hard for managers to justify this level of monitoring across their preserves. Active monitoring is far more costly, requiring special training, permits, and constant travel to and from trap locations. Partnerships with the USDA APHIS (Animal and Plant Health Inspection Service) or state agencies may be a more viable way to achieve a similar level of surveillance monitoring on TNC's preserves, especially when collaborations to secure grants or mutually funded programs exist.

Realistic goals for the prevention, control, or management of invasive animal species are important. Some species are fully established or have become naturalized (e.g., European starlings) and are beyond the point of effective control. Others are established but pose enough threat to TNC preserves that controlling them within sensitive areas may be worth the effort (e.g., local exclusion of feral pigs). Tracking many of the other ecosystem response metrics discussed in this document will help inform whether management efforts are being effective.

Table 5.3.2. Supporting science and existing planning tools for invasive animals.

Name	Summary
National Invasive Species Information Center (NISIC)	USDA portal for all things invasive species
NISIC Invasive Species Profile page	Summary page within USDA portal about various invasive species by group (aquatic plants, invertebrates, vertebrates, etc.)
Center for Invasive Species and Ecosystem Health – Global	Invasive species catalog w/ links to known ranges of species as well as biology papers, control papers, etc.
Florida Fish and Wildlife information page on non-native fish and wildlife	State agency portal to info on non-native invasive animals
TNC Stewardship calculator	TNC created budgeting tool for long-term stewardship actions

5.3.3 Overabundant large ungulate browse impacts

Why are overabundant large ungulate browse impacts an important management consideration for reducing stress on site resilience in terms of biodiversity, productivity and/or ecosystem function?

Pervasive and persistent white-tailed deer (*Odocoileus virginianus*) and other large ungulates' browse of tree seedlings and understory vegetation alters forest ecosystem processes and diversity, making it difficult for forests to regenerate following overstory disturbance (Rooney and Waller 2003). Persistent white-tailed deer browse reduces forest regeneration abundance and diversity. Tree seedling abundance generally decreased as deer density increased above 5.8 deer km^2 (Russel et al. 2016). Poor regeneration can lead to poor to moderate forest stocking and lower productivity and sequestration of carbon. In areas with chronic white-tailed deer overbrowsing of preferred nutritive tree seedlings and plants, there is often a shift in vegetation composition to less preferred, and often invasive, tree and plant species with little or no nutritive value. This leads to a reduction in plant and tree species diversity (Horsley et al. 2003; Ward et al. 2018), which can influence long-term resilience. In areas with high moose populations, excessive browse and barking of hardwoods leads to forests of poor quality, suppressed trees that may never increase in volume due to repeated defoliation.

Moderate or high ungulate herbivory is widespread throughout the Midwest and Northeast (McWilliams et al. 2017) and also occurs in parts of the Rocky Mountains, Southwest, and Interior West.

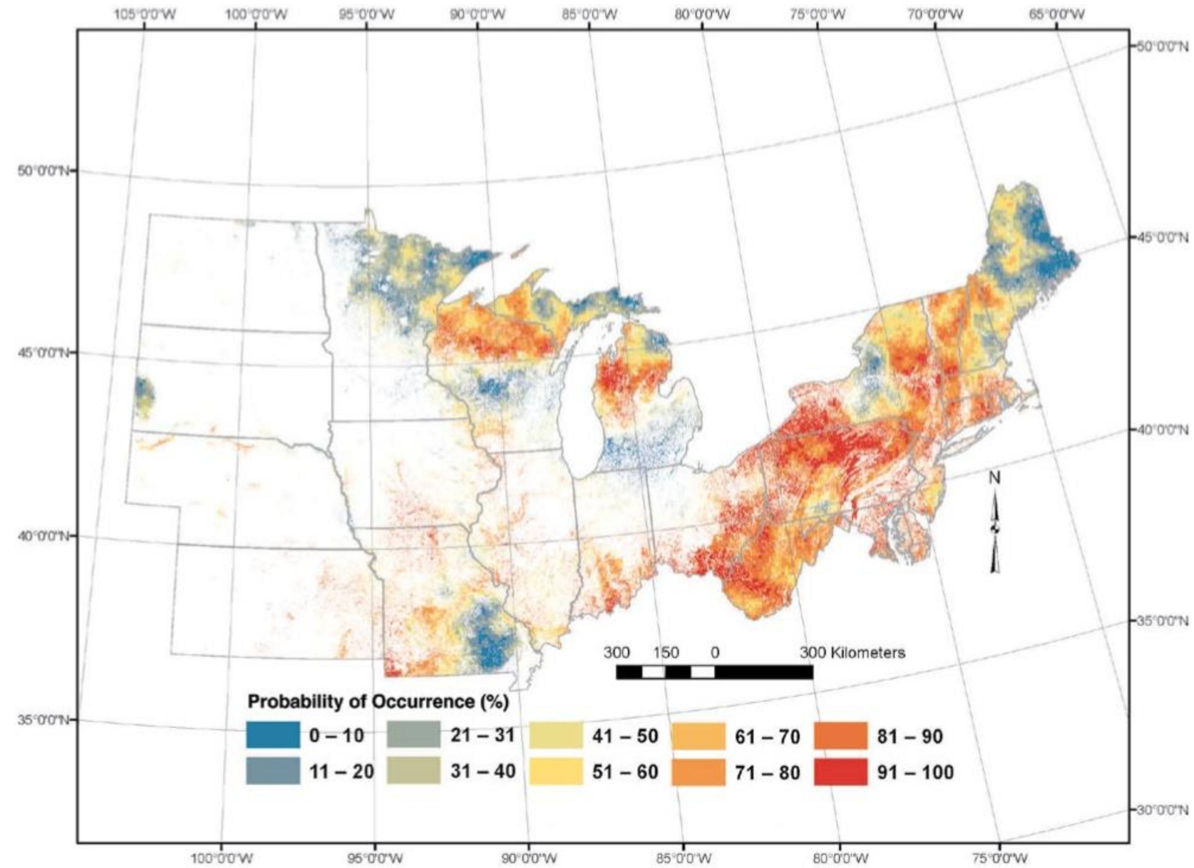

Figure 5.3.3. Probability of occurrence for moderate or high ungulate herbivory risk on forest land, Midwest and Northeast (McWilliams et al. 2017).

What are expected climate change impacts on overabundant large ungulate browse impacts?

The Pennsylvania Deer-Forest Study summarized the potential influence of climate change on the abundance of white-tailed deer (Diefenbach 2015). In the northern part of the eastern region (Northern Appalachians) winter kill is a predominant factor in population mortality and growth. A study in Minnesota found that 50% of the variation in adult female mortality is explained by winter severity (Delgiudice et al. 2006). White-tailed deer populations will likely increase in northern regions as winter temperatures increase and snow depth decreases due to climate change. However, diseases and ticks that influence deer herd health may increase with warmer and wetter summers. Conversely, increased temperatures may have an adverse impact on moose populations with expected northward movement of their range as temperatures increase. This, combined with the increase in stress from high winter tick infestations, has had a localized adverse impact on moose.

What are potential methods to make the system more resilient to overabundant large ungulate browse impacts?

Several TNC operating units have deer management programs and their success in mitigating browse impacts likely varies based on a range of conditions. Deer exclosures exist on numerous TNC preserves to demonstrate the density and diversity of forest vegetation in response to excessive browse. Deer management on TNC lands with high browse impacts will likely require multiple strategies to sustain resources and achieve success.

What should we be looking for when we monitor to know if resilience is enhanced? What are useful thresholds to apply?

The impacts of white-tailed deer browse on tree seedling and spring wildflower growth can be monitored to evaluate change over time. See the AVID protocol: Assessing Vegetation for Impacts from Deer. Some TNC deer management programs have used pellet counts, infrared-triggered cameras, and aerial infrared surveys to estimate changes in deer population numbers. The USFS evaluated the success of a cooperative deer management program in Pennsylvania using multiple techniques (Stout et al. 2013). Moose impacts can be monitored using photo plots to determine browse impacts over time and compared with moose population estimates determined by state game agencies.

5.3.4 Invasive pests and pathogens

Why are invasive pests and pathogens an important management consideration for reducing stress on site resilience in terms of biodiversity, productivity and/or ecosystem function?

Invasive, non-native, forest pests and pathogens are one of the only environmental stressors in the world that are capable of rapidly removing entire genera and species of trees from whole ecoregions over the relatively short course of a single human lifespan. North America has seen the functional extinction of two ecologically dominant tree species in the last 150 years (American chestnut and American elm) due to invasive forest pests and pathogens, and the progressive elimination of other species and genera from entire regions and ecosystems is currently underway. Most notable among the genera and species now in sharp decline and threatened with elimination from eastern North America include ash species east of the Continental Divide (*Fraxinus* spp.), eastern and Carolina hemlocks (*Tsuga* spp.), redbay (*Persea borbonica*) and five-needle pine (e.g., *Pinus strobus*) stands at high elevations. The subsequent loss of nearly all associated specialist species of insects and wildlife that depend on these trees further compounds the losses that forest pests and pathogens exact on native biodiversity. The aggregate loss of forest diversity is even more serious when assessed over a series of invasions; eastern hardwood forests especially have faced a historical barrage of tree-killing invasive species for over 100 years. In a forest where multiple tree species are extirpated from interrelated niches over time (such as canopy, riparian, and understory), all the broadest metrics of ecosystem health can be simultaneously negatively impacted- ecosystem function, net productivity, species diversity, water quality, etc. Impacts on human communities in the form of reduced ecosystem services and exorbitant mitigation costs are also important.

Invasive forest pests and pathogens are also capable of converting forest stands from carbon sinks to carbon sources for times scales of years to decades (Fei et al. 2019;

Kurz et al. 2008; Quirion et al. in prep). For this reason, they could upend and defeat strategies to mitigate CO_2 emissions- effectively negating the efforts by TNC NAR's Natural Climate Solutions to restore forests and expand the extent of forest lands (Griscom et al. 2017). Evidence from studies in Europe and North America indicate that both native and invasive non-native forest pests and pathogens are already causing measurable decreases in forest carbon storage and sequestration rates (Clark et al. 2010; Flower et al. 2013; Seidl et al. 2018). In other words, forest pests and pathogens are already reducing the capacity of forests to mitigate climate change. Some published studies demonstrate the capacity of forest pests and pathogens to transform forests that have historically acted as carbon sinks into carbon sources; they show that it takes several decades or more until tree regeneration replaces the carbon lost by damaged or killed stands. Unfortunately, new non-native forest pests and pathogens continue to be introduced to North America at alarming rates (Aukema et al. 2011; Lovett et al. 2016). Leung et al. (2014) assessed recent rates of introductions of wood-boring insects to the US and predicted that without improvements in preventive measures, more than 300 new non-native pest species could be expected to become established in the US by 2050. This is likely commensurate with rapid expansions in globalized trade and the intercontinental transport of wood packing material.

What are expected climate change impacts on invasive pests and pathogens?

Climate change is already allowing invasive forest pests and pathogens to expand their ranges northwards and into higher altitudes. In addition, the forest pest species native to North America are reaching farther north, and some are starting to exhibit impacts similar to non-native forest pests in these new areas. For instance, mountain pine beetle and southern pine beetle have expanded northwards to vast areas they formerly didn't reach in the northern & Canadian Rockies and in Northeastern US forests respectively (Dodds et al. 2018). Non-native invasive forest pests such as white pine blister rust (*Cronartium ribicola*) and hemlock woolly adelgid (*Adelges tsugae*) are also expanding northward as cold temperature barriers that prevented these movements likewise shift to higher altitudes or latitudes. More frequent droughts and fewer cold nights are also reducing the limiting factors of some invasive forest pests - further exacerbating pest population cycling and expanding geographic ranges largely northward.

Due to the shifting baseline effect, land managers may not realize that many Eastern forests, and some high elevation Western forests, are already suffering from the historic loss of key canopy species such as American elm and chestnut- making the protection of remaining tree species diversity all the more critical.

What are potential methods to make the forested systems more resilient to invasive pests and pathogens?

Planning for the prevention of new forest pests and pathogens, as well as the management of newly arriving and established pests and pathogens, will be crucial to manage for resilience in any forested ecosystem. Facilitating the recruitment of remaining native tree species and, in some cases, introduction of new native ones likely to expand their ranges as a result of climate change will also be essential for filling canopy gaps and maintaining forest resilience. However, due to the persistence of pests and pathogens in the landscape and the difficulty of landscape level prevention, these tactics will need to be complimented by host tree species recovery/resistance programs.

The most powerful on-the-ground TNC contributions to long term resilience to the threat of invasive forest pests may prove to be in actively managed recovery programs for affected tree species. With the knowledge, capacity, private ownership, and organizational infrastructure afforded to our land managers, TNC is outstandingly well suited to participate in regional, federal, or continent-wide multi-stakeholder species preservation and replanting efforts. The forest pest and pathogen long term response efforts best suited to TNC lands for any given threat will vary, but most fall into three broad categories; identification, collection, and breeding of resistant individuals within an affected species or genus within large scale recovery programs (i.e., USFS breeding efforts); seed (or other plant material) collection for preservation of genetic diversity at landscape scale in partnership with regional seed or genetic banking efforts; and experimental or early-operational replanting of affected sites with resistant, hybridized, or genetically modified stock.

Due to the nature of the pathways and biological characteristics of invasive forest pests and pathogens, many important preventative actions and strategies taken by TNC to manage this threat are not feasible nor relevant at the preserve or state chapter level. Other organizational levels of TNC – such as North America Region's Natural Climate Solutions and North America Policy and Government Relations – are engaging in efforts that prevent, manage, and promote recovery from non-native forest insects and diseases. These efforts include- advocating for research on host tree resistance, gene editing of host trees, biocontrol development, and innovative early detection tools; recommending changes and improvements to federal prevention programs within the global supply chain to prevent the introduction of additional non-native forest insects within that pathway; advocating for federal funding of key programs such as biocontrol research, early detection, and the eradication of certain high impact pests.

What should we be looking for when we monitor to know if resilience is enhanced? What are useful thresholds to apply?

Lingering individual host trees that remain after an infestation of forest pests or pathogens represent an enormous opportunity for understanding resilience in the face of invasive pest and pathogen threats. Surviving trees typically represent some combination of resistant genetics, site characteristics that promote survival, or variations in pest or pathogen characteristics over space or time (such as an emerging biocontrol or competitor, or changes in virulence due to climatic factors). TNC's ability to leverage our longstanding monitoring of site conditions to aid regional or national research or recovery programs is a very powerful asset in long term species resilience and recovery programs. Looking for, identifying, and reporting, lingering trees or stands is a keystone concept for several current programs (elm, chestnut, ash, and hemlock) and determining if your preserve or state can participate in current regional or national recovery programs is an important first step in crafting a useful monitoring plan.

Some, but not all, invasive species can be effectively managed on the site level. Proactive research on potential threats in your area (for instance, determining what percentage of your forest canopy is hemlocks) can then allow you to prioritize monitoring while researching the most up to date management techniques. The field of forest invasive species management is moving forward very rapidly- advances in biocontrol, pesticide type and usage, and site-specific management are occurring at a startling pace. Therefore, understanding the current state of the science and how you might apply it, when the time comes, will allow you to manage your site for long term tree diversity in the face of this challenge.

Resources

- For a seminal overview of forest pest economic damage, see: https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0024587
- For a recent study on how tree diversity can regulate invasive pests: https://www.sciencedaily.com/releases/2019/03/190325151014.htm
- To consider the consequences of a functionally extinct species in hardwood forests, with a focus on practical restoration: https://www.researchgate.net/publication/288072884_Consequences_of_Shifts_in_Abundance_and_Distribution_of_American_Chestnut_for_Restoration_of_a_Foundation_Forest_Tree
- Effects of drought and forest pests on tree mortality. Kolb, T. E., Fettig, C. J., Ayres, M. P., Bentz, B. J., Hicke, J. A., Mathiasen, R., ... & Weed, A. S. (2016). Observed and anticipated impacts of drought on forest

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- Fragmentation effects on insect and disease invasion https://www.srs.fs.usda.gov/pubs/58156

APPENDICES

APPENDIX A: Climate Change Vulnerability Assessment Frameworks and Resources

Managers often want to know how vulnerable the species or ecosystems they steward are to climate change and several frameworks exist for estimating their vulnerability. The basic approach is to quantify the major components of risk - sensitivity, exposure, and adaptive capacity - either by assessing relevant traits (Glick et al. 2011; Chin et al. 2010; Arribas et al. 2012; Gardali et al. 2012; Foden et al. 2013) or measuring historic trends and correlations (Thomas et al. 2011; Triviño et al. 2013; Young et al. 2012; Pearce-Higgins et al. 2015). Vulnerability frameworks provide a logical and organized way for considering the potential vulnerabilities of species we manage and as a result they have been incorporated directly into many widely used agency frameworks. Although vulnerability assessments have been completed for most of the US, only recently have they been systematically tested to identify the best methods and assess their usefulness in predicting changes in distribution or abundance.

The following resources provide helpful information on assessing vulnerability.

External Vulnerability Assessment Resources
CLIMATE CHANGE RESPONSE FRAMEWORK The **Climate Change Response Framework** (CCRP; forestadaptation.org) provides a range of resources for land managers. The "Explore Climate Impacts" webpage hosted on the site provides a summary of climate impacts for regions covering the entire United States with links to source published reports. For those land managers using the CCRP's Adaptation Workbook, the summary of climate impacts will automatically populate in your online workbook based on the site location. In the context of assessing exposures, ecoregional vulnerability assessments are available in several formats for areas in the Northeast and Midwest. These assessments provide overviews of observed climate change and projected changes in climate and physical processes with charts and maps. The NIACS **Climate Change Response Framework Ecosystem Vulnerability** page provides portals to vulnerability assessments focused on forested ecosystems across 8 regions in the Northeast and northern Midwest. For managers outside those regions, the site's **Resource Finder** may help you locate similar materials for your site. The materials vary by region, but they compile and summarize findings about how sites are vulnerable and the capacity for regional adaptation. The New England and Northern New York region has a *Climate Change and Adaptation story map* that includes a tab on Forest Vulnerability by forest type.
National Climate Assessment The **National Climate Assessment** (NCA; https://nca2018.globalchange.gov/) is the definitive summary of climate research in the United States. Regional assessments provide general source material for many resources, and the maps and graphs provided may be helpful. It also provides linkages to key messages

across the report and its comprehensive review of the published source material.

The National Climate Assessment's Regional Assessments provide general vulnerability information and overviews of exposures (keep in mind that the assessment was published in 2014).

NatureServe
Connecting Science With Conservation

The **NatureServe Climate Change Vulnerability Index** provides a tool for species-specific assessments of vulnerability to climate change. If you are particularly concerned about the sensitivity and adaptive capacity of certain species on your site, you may decide that it is worthwhile to invest some time to understand and download this tool.

National Centers for Environmental Information
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

The **NOAA 1991-2020 U.S. Climate Normals Quick Access** provides access to data from the most recent version of the U.S. Climate Normals. This iteration of the Normals product provides 30-year averages of temperature, precipitation, and other climate variables, as well as set of 15-year supplemental normals for 2006–2020. These are useful because they show the actual temperature and moisture changes over the last century.

WORLD BANK GROUP
Climate Change Knowledge Portal
Climate Analysis Tool - Powered by Climate Wizard

The **ClimateWizard** allows users to select a polygon on the landscape and receive an email with the climate variables and data selected. It provides technical and non-technical audiences with a visual mapping tool to access historical and projected changes in annual temperatures and precipitation levels for any geographic location worldwide.

USGS
science for a changing world

The **United States Geological Survey National Climate Viewer** provides visual information about historical and future modeled climate and water conditions for both a medium (RCP 4.5) and high (RCP 8.5) emissions scenario. Note that the viewer may be unavailable until it is reprogrammed to work without the Adobe Flash Player.

Climate Change Atlas

The **U.S. Forest Service's Climate Change Atlas** contains the current and possible future distribution of 134 tree species and 147 bird species in the Eastern United States and gives detailed information on environmental characteristics defining these distributions. It also serves as a portal to other resources related primarily to forest vulnerability, as well as summaries of climate exposures based on forest location.

CLIMATE CHANGE
RESOURCE CENTER

The U.S. Forest Service **Climate Change Resource Center** provides links to other climate change data sources, including specialized portals for freezing level, drought, and snow.

An important consideration in reviewing climate change resources that can be overlooked is how seasonality and rates of change could vary over time. Since climate change will affect each site in many interconnected ways, it's important to think about which components and processes are priorities as you assess vulnerabilities and develop management strategies to address them.

It may also be helpful to review data, information, and even anecdotal evidence about how the site has changed over time. For example, you might have information or inferences about how soil moisture, floodwater storage, red maple abundance, or habitat connectivity have already changed (major influences may be unrelated to climate change but can provide insight into how the site will react to future conditions). These questions may help managers in further assessing exposures beyond the general information provided by resources like those above or others available for your specific site, region, or state. While the answers may be largely unknown, they may be able to guide your approach to thinking about how you manage the site.

- How much change (in temperature, precipitation, sea-level rise, etc.) has the site already seen since a baseline year? How does that rate of change compare to the rate of change expected in the next 10 to 30 years? See the NOAA Climate Normals site in the table above for data.
- How have recent extreme events and/or outlier years impacted the site? Could this provide reference for how the site might be sensitive to future events or climate changes?
- How might the seasonality of specific climate impacts affect the site? It's important to keep in mind that warming or increased precipitation are often more pronounced in specific seasons depending on location.

While understanding relatively subtle changes from past years and between seasons could be very beneficial for land management planning, the more drastic climate effects projected in the latter half of the 21st century (especially under high-emissions scenarios) may not merit the same level of analysis. Site managers are likely interested in projected exposures on their sites until 2050. Exposures in this time frame are not likely to be sensitive to emissions scenarios. In other words, whether humans drastically reduce greenhouse gases in the short-term will not have a major effect on impacts from climate change over the next thirty years.

An understanding that change will continue well into the future (for example, the sea level will likely continue to rise for hundreds of years from baked-in warming [Mengel et al. 2018]) should be considered during the site assessment process. Managers should prioritize flexible and no-regrets strategies that are not dependent on long-term projections. A qualitative understanding of how future climate change exposure in the second half of the 21st century might affect your site should inform your plans, but there is no need to assess exposure based on quantitative climate projections in forty years or more.

APPENDIX B: Evaluating Climate Change Vulnerability Assessments

Vulnerability assessments are complementary to managing for resilience with the former being species or ecosystem specific, and the latter being site specific and spatially explicit. However, thirty years of practice has revealed a host of inconsistencies and issues with the vulnerability approach. The pros and cons are reviewed in Foden et al., (2018) along with extensive recommendations for improving their utility and accuracy. A few of the major issues are discussed below.

Trait-based vulnerability frameworks consider each species' life history characteristics and range limits to infer the probability of risk to the species under a changing climate. The value of trait-based assessments has come into question after a study tested the results from 12 vulnerability frameworks against long term historic data on birds and butterflies in Britain and found the trait-based ones to be poor predictors of risk and inconsistent among themselves (Wheatley et al. 2016). Out of 219 species tested, 54% were classified as high risk by at least one framework, and only 6% were classified in the same category by all frameworks. Further, the ability of the trait-based assessments to predict changes in the distribution or abundance of the species tested was non-significant or worse-than-random in every case.

Trend-based vulnerability frameworks use historic or modeled abundance and distribution changes to predict future trends, and they perform better than trait-based models as predictors of change in response to climate. In the British study, two of the trend-based approaches showed statistically significant predictive power on response variables in the bird and butterfly data (Wheatley et al. 2016). One of the best performing, Thomas et al. (2011), used the level of climate-related decline within a species' recently occupied distribution based on observed and/or projected changes, as well as opportunities created by climate change measured as observed and/or projected increases outside the recently occupied historical range. Managers serious about assessing potential declines or increases in certain species should search for evidence of climate-based declines within their landscape of interest and consider developing a trend-based assessment of vulnerability.

While Resilient and Connected Network science should guide your site prioritization and selection process, it may be worth revisiting resources like the Resilient Land Mapping Tool to understand the vulnerability and adaptive capacity of your site in the context of the broader landscape.

Resilience and vulnerability information has been summarized in the "Designing Actions" section of this guidance. Each sub-chapter focuses on one feature of the geophysical landscape, system, or species.

APPENDIX C: Additional context on specific management approaches to manage for climate resilience

Reversing degradation, restoring processes through limited interventions, and thoughtful monitoring are essential for managing terrestrial systems for resilience, but what exactly do those actions look like?

In Section 2, we presented the core principles of resilience management. Characteristics that enhance a system's ability to change and adapt have been directly and indirectly studied through research on climate responses, catastrophic disturbances, and restoration. Sustaining or enhancing these characteristics is the objective of the management strategies that follow. In Section 4.2, we presented three categories of strategies: 1) those that create options for species to adjust, change, or avoid risk, 2) those that reverse abiotic degradation or restore processes, and 3) those that sustain the sources of biotic response.

The US Forest Service's Northern Institute of Applied Climate Science (NIACS) has developed a list of specific management strategies aimed at providing climate change approaches for land managers. We cross-walked their list into our framework based on whether the strategy focused on increasing options, restoring processes, or protecting sources of renewal (Table C). The exercise revealed that many of the NIACS management strategies are also aimed at sustaining, improving, or restoring these characteristics.

The NIACS framework, however, includes actions and recommendations that do not fit the category of site-based resilience strategies. These include what NIACS calls "resistance strategies" such as reducing the impact of existing biological stressors. These strategies may buy time by decreasing the exposure of the system to the stress, but because there is no inherent increase in resilience, the system is just as vulnerable to the stress the next time it is exposed to it. "Response strategies" defined by planting or management based on the expected future climate conditions overlap with our concept of providing biotic sources of renewal. The two strategies may differ only in the degree to which a manager allows the system to sort out its species composition and structure, or focuses on manipulating it to achieve a particular effect (e.g., removing existing invasives, favoring native species that are better adapted to future conditions, and managing for species with wide moisture and temperature tolerances). As they differ in concept from the approach we develop here, we encourage more dialogue on how they might fit within a framework of limiting interventions and letting natural processes drive adaptation.

A third set of NIACS strategies that we omit but strongly support are those aimed at conservation planning across a network of sites (e.g., ecosystem redundancy and landscape connectivity). These include specific recommendation to maintain or create refugia, prioritize and protect sensitive or at-risk species or communities, establish reserves to protect ecosystem diversity, increase ecosystem redundancy across the landscape, and expand reserves and reserve networks to link habitats and protect key communities. Although these are not site-based management strategies, they are an important part of a climate change response. The NIACS strategy to identify and prioritize sites expected to be buffered from climate change is similar to TNC's work to identify and protect resilient connected micro-climates that buffer resident species from the regional climate (Anderson et al. 2014).

Another prominent decision-making framework for climate adaptation is the "Resist-Accept-Direct" (RAD) framework, recently popularized by the National Park Service. This framework is similar to the one proposed by TNC in many ways, but differs subtly in two regards. The first is that it is primarily oriented around actions, not outcomes, while TNC's framework explicitly includes outcomes, defined as resilient sites and systems. This leads to the second distinction, which is that under the RAD framework, many actions that TNC would consider essential for resilience, such as restoring Nature's Stage, are most readily placed in the Resistance category. TNC differentiates between actions that resist the influence of climate change on the composition, structure, and function of a site and actions that are necessary to restore processes that increase the long-term resilience of the site.

A third framework that TNC land managers may encounter, particularly when working with partners at the Wildlife Conservation Society (WCS), is the R-R-T scale (resistance-resilience-transformation) proposed by Peterson St-Laurent et al. (2021). Like TNC's framework, the R-R-T scale integrates actions and outcomes, but it was developed with the intent of evaluating actions along a six-point spectrum that ranges from actively resisting change to accelerating transformation towards "new, more climate adapted conditions." The primary distinction is that this framework takes a narrow view of resilience, considering it as "Actions designed to improve the capacity of a system to return to desired past or current structures and functions following a disturbance…while recognizing that some new elements are inevitable." As mentioned above, TNC merges 'resilience' and 'transformation' because disturbance in the context of continued change of ambient conditions will inevitably lead to transformation. In this sense, TNC's treatment of managing for resilience is synonymous with several actions on the R-R-T scale, including "Autonomous transformation," "Directed Transformation," and "Accelerated Transformation."

See Table C on the next page for examples of management approaches under different management approaches.

Table C. Examples of options, processes and sources. Note: The fourth column integrates the Northern Institute of Applied Climate Science (NIACS) specific management approaches (marked with asterisks) in addition to our own recommendations (Anderson et al. 2016).

Element of Site Resilience	Strategy Objective	General Strategy	Specific Management Approaches (* = NIACS)
Options	Increase climate and movement options and spread risk	Identify and protect microclimates	Manage habitats over a range of sites and conditions* Protect and connect areas with microclimates created by topography and elevation
		Promote local connectedness	Reduce fragmentation and enhance connectivity* Maintain and create habitat corridors through reforestation or restoration* Protect and connect riparian areas
		Increase reserve size	Expand the boundaries of reserves to increase diversity, buffer against disturbance and link microclimates Prepare for more frequent and more severe disturbance*
		Enhance age/size class diversity*	Promote diverse age-classes including very old trees*
		Promote and connect geophysical diversity	Protect and connect areas with a diversity of bedrocks and soils
		Maintain and enhance species diversity*	Maintain and restore diversity of native species* Introduce seeds and other genetic material from across a greater geographic range* Increase diversity of nursery stock to provide a greater range of species or genotype* Allow and encourage new mixes of native species*
Process	Reduce physical degradation and Manage for self-perpetuating processes	Reduce physical and chemical degradation	Ensure that water quality and soil PH are not compromised by excessive anthropogenic inputs
		Sustain natural fire regime	Restore fire to fire-adapted ecosystems through limited interventions* Alter forest structure or composition to reduce severity of fire if site has a history of fire suppression.* Establish strategic fuel breaks to slow the spread of catastrophic wildfire
		Maintain unimpaired hydrology	Maintain or restore natural unimpaired hydrology* Maintain or restore riparian areas* Retain water on-site using natural stuctures that prevent excess runoff Remove hydologic barriers and allow for periodic flooding where appropriate
		Ensure periodic recruitment	Manage herbivory if needed to protect and promote regeneration* Monitor regeneration and use limited interventions when needed to facilitate establishment.
		Enhance soil forming processes	Maintain or restore soil quality and nutrient cycling* Ensure adequate supply of organic matter (litter, fine and coarse woody debris) is being returned to soil
		Allow natural gap dynamics	Plan for and allow periodic wind and ice damage Leave large woody debris, tip up mounds and other residuals as a legacies
		Restore keystone species	Restore pollinators, builders (beavers), filters (clams), canivores if needed
Sources	Nurture sources of biotic renewal	Retain and promote biological legacies*	Ensure large coarse woody debris is distributed across site Ensure streams have sources of woody debris adjacent to channel Ensure snags, nurselogs, wildlife trees are present on site
		Promote existing species populations	Promote existing populations of specialist species Improve populations of sensitive, at-risk , and displaced species*
		Promote immigration through landscape-level connectivity	Establish and expand reserve networks to link habitats and protect key communities* Maintain and create habitat corridors or natural cover linkages through reforestation or restoration*
		Respond to, or simulate, disturbances while maintaining diversity and continuity	Enhance natural seedbanks Maintain seed or nursery stock of desired species for use following severe disturbance* Allow for areas of natural regeneration after disturbance
		Introduce species when needed	If site is isolated from other sites by fragmentation, consider introducing suitable native species which would likely thrive in response to the site characteristics and current or future climates Introduce native genotypes that may be resistant to expected pests and pathogens

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