10th ANNIVERSARY

VERMONT ATLAS OF LIFE

REPORT

VERMONT CENTER FOR ECOSTUDIES
VERMONT ATLAS OF LIFE

Contents

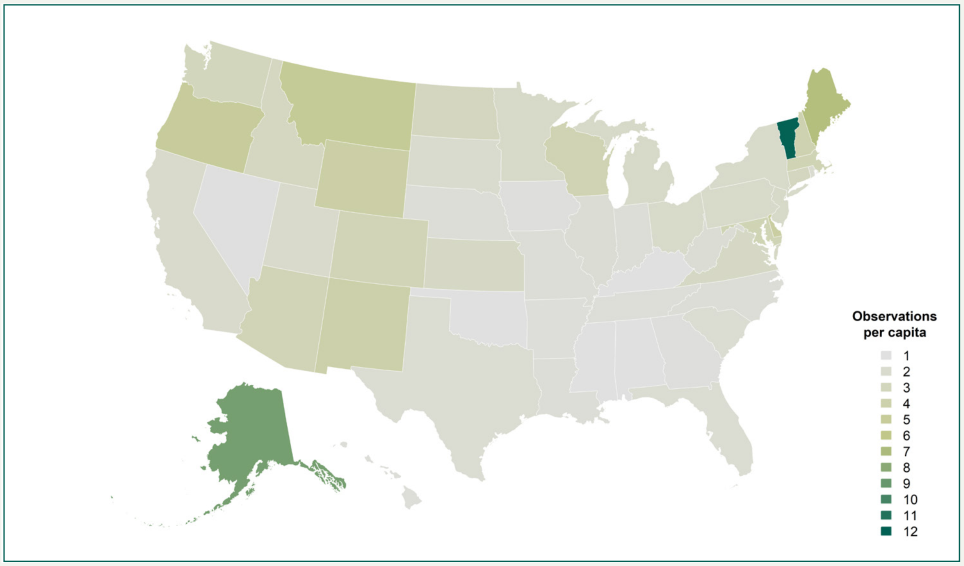
Executive Summary

A decade ago, the Vermont Center for Ecostudies launched the Vermont Atlas of Life (VAL) to aggregate data on species in Vermont and begin filling gaps in our collective knowledge. Over the last 10 years, VAL has amassed nearly 8 million species observations and grown into a central library of primary biodiversity data, accumulating knowledge from the past and present.

At VAL's core is the community of people contributing and using information about Vermont's changing nature: occurrence records, population data, distribution maps, photographs, and other data—from backyard naturalists to scientists to policymakers. In short, VAL is one of the most ambitious and far-reaching biodiversity informatics projects ever undertaken in Vermont. The Vermont Atlas of Life is giving us a better understanding of what's here, what's not, and how biodiversity and species distributions change over time.

As human activity profoundly alters the map of life at local and global scales, humanity's response requires knowledge of plant and animal distributions across vast landscapes and over long periods of time. Addressing threats to biodiversity requires foundational knowledge of what lives here and what we stand to lose if carbon emissions and environmental degradation patterns remain unchanged. Despite Vermont's rural and verdant character, it isn't isolated from global change and, in many ways, offers a microcosm where we can monitor biodiversity and implement conservation actions that others might apply at their own scales elsewhere.

Over the past century, we've likely recorded nearly every bird species that has flown in Vermont (382 species) and every mammal (58 species) that has inhabited the state. However, many other groups remain an enigma. Vermont's invertebrate diversity alone may approach 22,000 species, but no one really knows. Furthermore, for most species and many groups



Community scientists in Vermont lead the nation with more biodiversity observations shared per capita with VAL and the Global Biodiversity Information Facility than any other state.

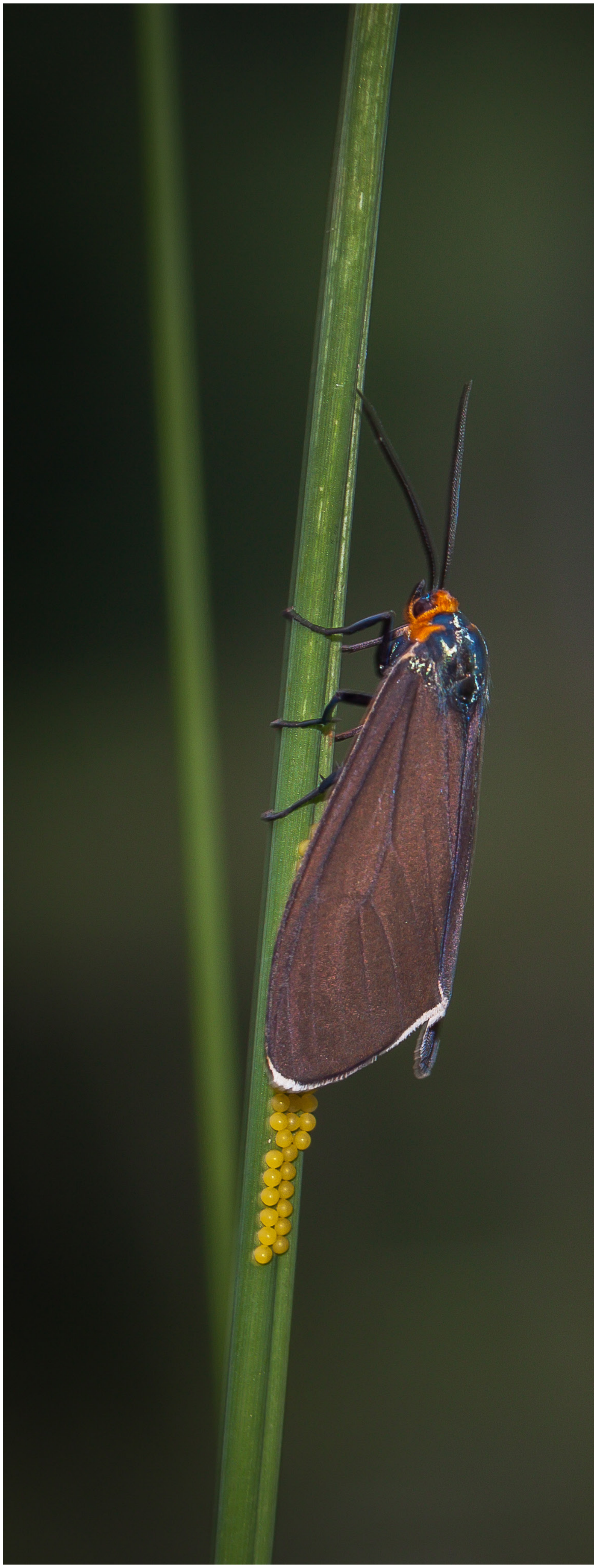
of organisms, no reliable assessments of their distribution or population trends exist. The Vermont Atlas of Life is helping to close that knowledge gap.

The *Vermont Atlas of Life 10th Anniversary Report* synthesizes VAL's efforts over the last decade of gathering data to help establish a biodiversity baseline for Vermont. This report uses nearly 8 million primary biodiversity occurrence records, totaling almost 12,000 verified species recorded across Vermont—all curated at the Global Biodiversity Information Facility (GBIF) and searchable using the VAL Data Explorer. Although these records are derived from many sources, from historical museum specimens to field observations, over 95% are submitted by community scientists through VAL-supported platforms like Vermont eBird, iNaturalist, and e-Butterfly. Vermonters have risen to the conservation challenge: our community scientists lead the nation with **more field observations per capita than any other state**.

High-quality biodiversity information is vital for science and conservation. One of the most critical components is primary biodiversity data. These data provide the basis for many quantitative studies that can inform effective regional and global conservation decisions. In this report, we draw upon Vermont's primary biodiversity data to better understand how many species there are and where they occur in the state. In some cases, we simply summarize the primary biodiversity data to determine what has already been observed. However, for most analyses, we couple primary biodiversity data with climate and other environmental data to generate species distribution models, allowing us to make inferences about what species may occur in areas of the state that are not well sampled. These models are essential for assessing conservation status and extinction risk, tracking population change, and guiding conservation efforts. They allow us to see Vermont's landscape in new ways, such as identifying potential biodiversity hotspots, understanding future impacts of climate change, targeting land conservation efforts, and so much more.

Key Findings

- The Vermont Atlas of Life has data for nearly 12,000 species across Vermont from 7.7 million occurrence records derived from museum specimens, photographs, and observations by biologists, naturalists, and community scientists.
- Our distribution models show that most species ranges are largely influenced by physical attributes of



the landscape, such as underlying bedrock and soil characteristics. For many taxa, bioclimatic variables associated with precipitation are more important than temperature for determining their distributions within Vermont.

- The International Union for Conservation of Nature (IUCN) lists 96 species found in Vermont that are of global conservation concern. Seven animal and three plant species are Federally Endangered.
- Only 28% of Vermont's species have a state conservation rank. There are entire taxonomic groups that have no conservation status assessment because of insufficient data. Over 200 species (164 plants and 53 animals) are listed by Vermont's Endangered Species Law.
- Vermont conservation lands, as currently configured, may not be adequately protecting at-risk species. The coverage area for at-risk species (Critically Imperiled: 12%, Imperiled: 17%, Vulnerable: 13%) was similar to species ranked as Secure (12%) or Apparently Secure (14%).
- Only a quarter of Vermont is conserved. By 2100, our current conservation lands will protect approximately 11% of species' ranges, down from 13% today. Private lands are and will continue to be key for conserving and supporting biodiversity into the future.
- By 2100, the number of species found in Vermont is expected to decline by at least 6%, a net loss of 386 species, under the current carbon emission scenario (RCP 8.5).
- Areas that support unique communities are critical for maintaining biodiversity in the state. The southern Lake Champlain Basin harbors the most unique communities of any region in Vermont. By 2100, higher elevations in the state are predicted to shelter more unique communities.
- Climate and land-use change present significant conservation challenges that require an understanding of species populations at large scales. Partnerships between scientists and the public, through the Vermont Atlas of Life, are providing key information now and peering far into the future.

Suggested citation: Hallworth, Michael T., Kent P. McFarland, Spencer Hardy, Nathaniel Sharp, Emily Anderson, Jason Loomis (2023). *Vermont Atlas of Life: 10th Anniversary Report.* Vermont Center for Ecostudies. https://doi.org/10.6084/m9.figshare.23498652.v1

Foreword

For a small state, Vermont packs a mighty punch in terms of documenting its biodiversity. No one does community science better, or has done it more consistently, than residents of the Green Mountain State. This report is a fitting testament to the long-standing legion of volunteer naturalists whose efforts underpin the Vermont Atlas of Life. As a regular myself in the community science trenches over the past 45+ years—though a "lightweight" compared to many practitioners—I can attest to the passion, commitment, perseverance, discipline, and sheer thrill of discovery that are the building blocks of this report.

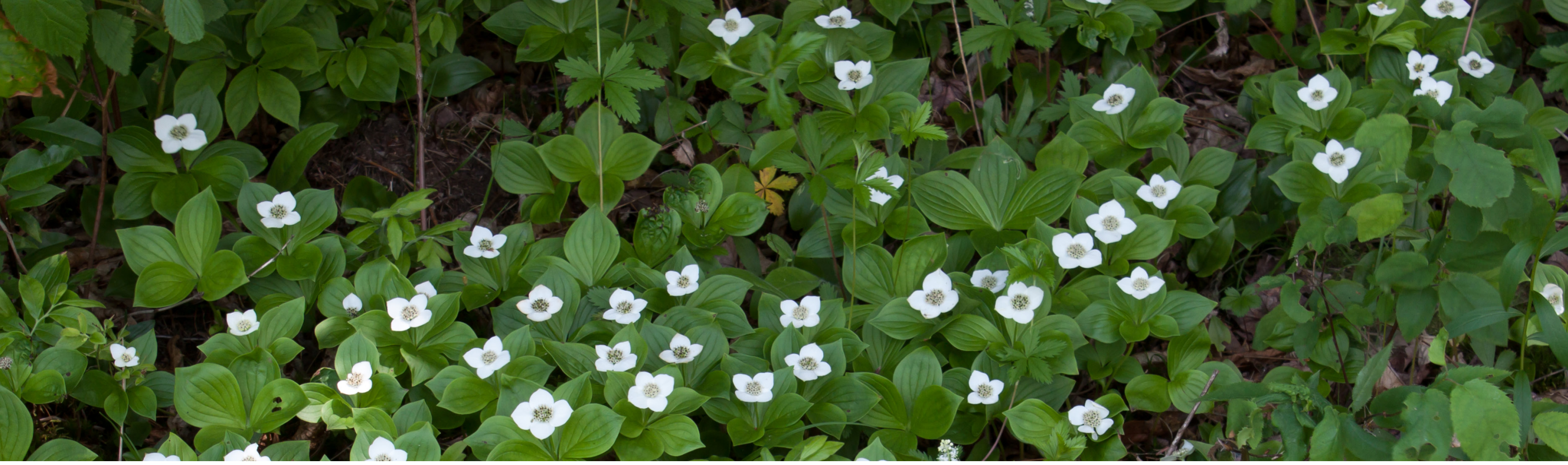
My own immersion as a community scientist began in 1977, as an undergrad at UVM, when I adopted a priority block in Milton for Vermont's first atlas of breeding birds. I was brand new to birding, had just switched my major from Classics (I kid you not!) to Wildlife Biology, and simply couldn't get enough of atlasing. I spent countless idyllic hours thrashing around Arrowhead Mountain and its environs. Four years later, Sally Laughlin at VINS hired me as one of six "blockbusters" in the final year of the atlas. I've never been paid to do something that was so much fun.

Fast forward to the present, and I find myself newly retired from VCE but no less beguiled by "naturalizing with a purpose" than I was four decades ago. The community science arena has exploded globally with the advent of crowd-sourced data collection, and Vermont continues to lead the charge. Our bragging rights are well-deserved and statistically sound, as no one tops us for per-capita use of iNaturalist, eBird, and e-Butterfly. VCE makes sure of that.

The Vermont Atlas of Life has firmly placed VCE and Vermont on the global biodiversity map. This bold, visionary effort to catalog every life form in Vermont—from nematodes to nymphalids, wild bees to warblers, and everything in between—is changing the way we humans observe, chronicle, and steward our planet's biodiversity. Together, VAL's community scientists have amassed 8 million records of over 14,000 species in Vermont alone. Combining VAL's myriad data sets with sophisticated analytical and modeling tools, we can now interpret changes that have already occurred, visualize them in detail, and predict future change scenarios. That is truly the stuff of on-the-ground, science-based conservation.

Sincere kudos to the VCE conservation science team for this extraordinary synthesis, but especially to all of us community scientists who have provided the grist with our hard-won discoveries. However, this is no time to relax; we've just scratched the surface of natural history work yet to do—bring on the second Vermont Butterfly Atlas and third-generation atlas of breeding birds!

Chris Rimmer
17 March 2023



Acknowledgments

The Vermont Atlas of Life wouldn't be possible without thousands of people dedicated to discovering and reporting the remarkable biodiversity we have in Vermont. More than 25,000 people have contributed data to one of our crowd-sourced projects, helped digitize historical records and specimens, or identified species from collections and images. Thank you for sharing your expertise and passion for the natural world with VAL.

Since we began Vermont eBird in 2003, more than 13,700 birders have contributed. We thank the bird data experts who spent countless hours helping to keep the data in order: Zac Cota, Sue Elliott, Kyle Jones, Craig Provost, Nathaniel Sharp, Ian Worley, Jacob Crawford, and Spencer Hardy. Every record entered into eBird is checked for accuracy, first by automated filters that flag unusual records and then by these expert reviewers who devote their personal time to ensure that the database is as accurate as possible. These organizations have helped to support Vermont eBird: Audubon Vermont, Ascutney Mountain Audubon Society, Birds of Vermont Museum, Friends of the Missisquoi National Wildlife Refuge, Green Mountain Audubon Society, North Branch Nature Center, Northeast Kingdom Audubon, Otter Creek Audubon Society, Rutland County Audubon Society, Southeastern Vermont Audubon Society, Taconic Tri-State Audubon Society, Vermont Fish & Wildlife Department-Habitat Stamp, and the Vermont Institute of Natural Science.

Since the inception of the Vermont Atlas of Life on iNaturalist in 2013, over 22,430 observers have contributed observations, and more than 13,000 people have helped to identify them. Some of them have gone to incredible lengths to help VAL. We can't thank these people enough. Thanks to Dan Lambert and Ryan Rebozo for carefully considering our work here and making excellent suggestions.

A project of this magnitude wouldn't be possible without the cooperation of many other organizations and government agencies. We'd like to especially thank the Vermont Fish & Wildlife Department, the University of Vermont Natural History Museum, iNaturalist, the Cornell Lab of Ornithology – eBird, Montreal Space for Life, the Global Biodiversity Information Facility, and the hundreds of institutions that have provided data from Vermont.

Major support for VAL has been provided by the Apis Fund, The Bailey Charitable Foundation, Binnacle Family Foundation, The Betsy and Jesse Fink Family Foundation, Charles E. & Edna T. Brundage Charitable Science & Wildlife Conservation Foundation, Growald Climate Fund, Horne Family Foundation, The Jack and Dorothy Byrne Foundation, Jane's Trust Foundation, The Kelsey Trust, Lintilhac Foundation, Richard Bowe and Karen Nemeth Fund at Fidelity Charitable, Riverledge Foundation, Ruml Leithner Family Fund, Vermont Fish & Wildlife Department State Wildlife Grants, The Sarah K. de Coizart Article TENTH Perpetual Charitable Trust, and other supporters of the Vermont Center for Ecostudies.

All photos in this report were taken by Spencer Hardy, Nathaniel Sharp, and Kent McFarland. Please contact the Vermont Center for Ecostudies before using any photos.

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Introduction

For centuries, humans have celebrated and documented the diversity of life that helps define Vermont. More recently, biologists, naturalists, students, and others have joined together to complete detailed statewide surveys or atlases of breeding birds, butterflies, wild bees, small mammals, reptiles, and amphibians, among others. Yet, these efforts represent a mere fraction of the state's natural heritage.

While we've likely recorded nearly every bird species that has flown in Vermont (382 species) and every mammal (58 species) that has crossed the state in the past 150 years, many other groups remain an enigma. Vermont's invertebrate diversity alone may approach 22,000 species, but no one really knows. And for most species and many groups of organisms, no reliable assessments of their distribution or population trends exist.

We cannot respond effectively to climate change, natural disasters, invasive species, and other environmental and economic threats without a deep understanding of the state's biodiversity.

A decade ago, the Vermont Center for Ecostudies launched the Vermont Atlas of Life (VAL) to gather data on species in Vermont and begin to fill knowledge gaps. The Vermont Atlas of Life is a central library of primary biodiversity data and accumulated knowledge from the past and present. At VAL's core are the community of people contributing and using information about the changing nature of Vermont: occurrence records, monitoring data, distribution maps, photographs, and other data free of charge to anyone—from backyard naturalists to scientists to policymakers. In short, VAL is one of the most ambitious and far-reaching biodiversity informatics projects Vermont has ever undertaken. From this information, we can begin to better understand what's here, what's not, and how biodiversity and species distributions change over time (Fig. 1).

In 2019, the United Nations Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services reported that global species extinction is accelerating and nature is declining at rates "unprecedented in human history," with as many as a million plant and animal species at risk of extinction, some within a few decades. The worldwide biodiversity crisis is driven by global change, which has accelerated over the past 50 years. We cannot respond effectively to climate change, natural disasters, invasive species, and other environmental and economic threats without a deep understanding of the state's biodiversity. Direct drivers of global change include land and sea use change, exploitation of natural resources, climate change, pollution, and invasive species.

As human activity profoundly alters the map of life at local and global scales, our response requires knowledge of plant and animal distributions across vast landscapes and over long periods of time. Despite its rural and verdant character, Vermont isn't isolated from global change. We cannot respond effectively to climate change, natural disasters, invasive species, and other environmental and economic threats without a deep understanding of the state's biodiversity. A key requirement is the availability of information on the status and trends of biodiversity in formats that are "easily understood, timely, scientifically rigorous, standardized, relevant, global, and representative of species populations across taxa and regions over time".[1]

Launched in 2013, VAL couples the power of community science with traditional research and monitoring to quantify biodiversity and change, now and into the future. The Vermont Atlas of Life joins others across the globe in curating primary occurrence records at the Global Biodiversity Information Facility (GBIF), an international network funded by the world's governments and aimed at providing anyone, anywhere, open access to biodiversity data.

Data sharing has become an important practice in modern biodiversity research to address large-scale questions and conserve species. Despite the steadily growing scientific and conservation demand, data are not always easily accessible. Worse, they may be lost forever if they are not properly archived.

The GBIF network includes hundreds of institutions that publish biodiversity data, like VAL. The GBIF provides data-holding institutions around the world with common standards and open-source tools that enable them to share information about where and when species have been recorded.

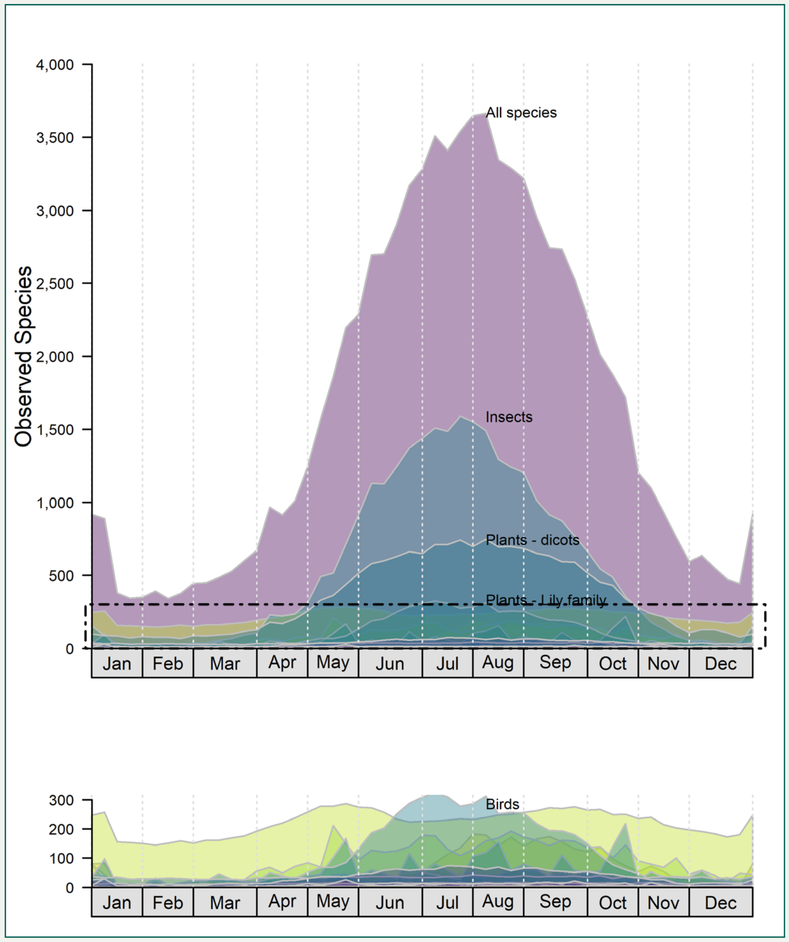


Figure 1. The number of observed species peaks dramatically each year with the growing season. Over 3,500 species have been recorded in July and August alone—many are plants or insects—while fewer than 500 species have been observed in February. The lower chart represents a closeup of taxonomic groups with fewer species.

Data found at VAL and GBIF are provided by a wide range of cooperating organizations, projects, individuals, community groups, community scientists, government agencies, and others. They may be from museum specimens collected as far back as the 1800s or verified observations by amateur naturalists shared with Vermont eBird, e-Butterfly, and iNaturalist just this year. The Vermont Atlas of Life works closely with data providers to assist them with better capturing, curating, managing, and sharing of biodiversity data.

The GBIF network draws all these sources together by using a data standard known as Darwin Core, which allows occurrence and biodiversity data from many different data publishers to work together seamlessly. These publishers provide open access to their datasets using Creative Commons license designations, allowing researchers to use the data in hundreds of peer-reviewed publications and policy papers each year. Many of these analyses—which cover topics from the impacts of climate change and the spread of invasive species to priorities for conservation and protected areas, food security, and human health—would not be possible without this.

For this report, we used nearly 7.7 million species occurrence records. These occurrence records come from a variety of sources, including historical museum specimens that have been digitized to contemporary community science platforms. Over the last decade, species occurrence records have been submitted from all corners of the state. In fact, occurrence records have been submitted from all 256 municipalities in Vermont, from the most populous to the several unincorporated towns without a human population. The town of Norwich had the most occurrence records with over 400,000 observations, while Baltimore, one of the smallest, had the fewest with 386, more observations than residents (382).

Vermont comes alive each spring with the return of migratory songbirds, blooming woodland wildflowers, forest canopies turning green, and Vermonters outside enjoying the flush of life. The number of occurrence records submitted between the start of May and the end of October reflects that, with growing season records dwarfing observations reported during the winter months. In fact, over 3,500 species have been recorded in July and August alone—many are plants or insects—while fewer than 500 species have been observed in February (Fig. 1). They all add up to nearly 12,000 verified species recorded across the state.

This report synthesizes VAL's efforts over the last decade of gathering data to help establish a biodiversity baseline—in other words, to document the state of biodiversity in Vermont. This information is needed to measure how multiple stressors, such as habitat modification and climate change, will impact Vermont's biodiversity so we can make informed decisions to conserve Vermont's natural heritage for future generations. Although this report is not a conservation strategy, its findings highlight priorities for building a future where both humans and nature can flourish in Vermont.

What is biodiversity?

Biodiversity, or biological diversity, refers to the variety of life in all its forms and all the interactions between living things and their environment. It includes ecosystem diversity, community diversity, species diversity, and genetic diversity. For the purposes of this report, however, we use the term more narrowly to describe the collection of all the species that reside in Vermont.

Tallying the species that live in Vermont is no simple task. For some groups of organisms, like birds, we have an in-depth understanding of where species occur and the habitats they use. Birds are relatively easy to count and observe because they are often conspicuous and can be identified by either sight or sound. It helps that just over 200 species are known to have nested in Vermont. By contrast, scientists often find insect species never before encountered in Vermont, including some that are completely new to science. Even insects may be relatively easy to count compared to Vermont's fungi or single-celled organisms, such as bacteria (Fig. 2).

The number of species in Vermont depends on how the word is defined. Throughout this report, we draw from taxonomic checklists used by GBIF and curated by the Integrated Taxonomic Information

System, the Catalogue of Life, and other biodiversity partnerships. These checklists are maintained by expert taxonomists from across the globe, who are dedicated to curating an up-to-date index of the Earth's known species.

There are many ways to count species. Within this report, we measure biodiversity using a few different metrics, such as *species richness*, which is synonymous with *alpha (α) diversity* and describes the number of species found at a particular location. The regional species pool or *gamma diversity (γ)* is a metric that includes all the species that occur within a region. Lastly, *beta diversity (β)* is a metric that describes species composition differences at sites within the same region. *Beta diversity* is a valuable metric for identifying sites with unique species compositions. Locations or sites with high *beta diversity* may not necessarily be speciose but instead may harbor rare species or support a species assemblage seldom found elsewhere.

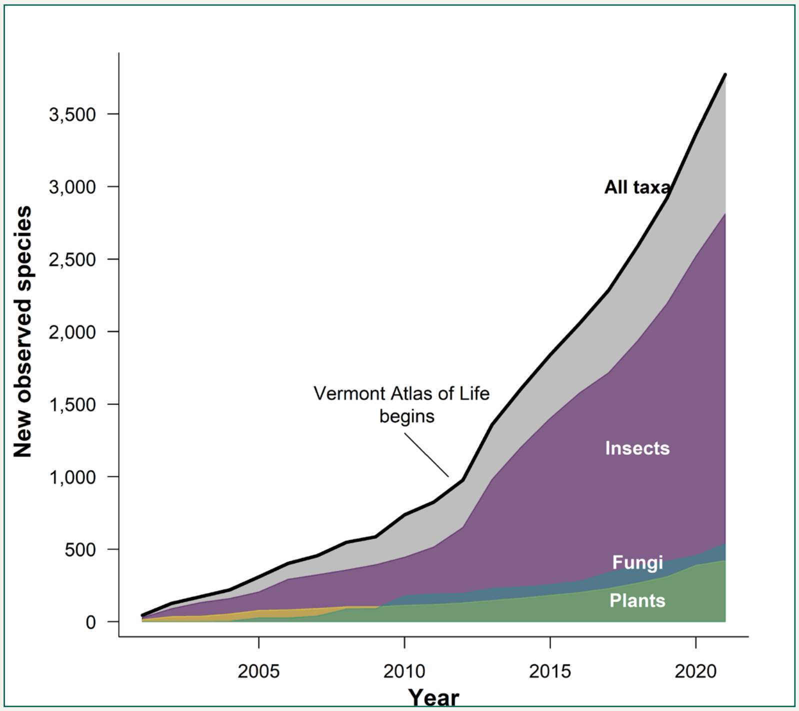


Figure 2. *The number of species observed for the first time increased sharply after the Vermont Atlas of Life project started. The popularity of iNaturalist diversified the taxon community scientists were submitting. The number of plant and fungi species first observed in Vermont has been increasing since VALs inception. However, the number of insect species reported for the first time grew exponentially for the first several years after VAL started and has been increasing ever since.*

We use *species accumulation curves*, also known as *collector's curves*, which illustrate the rate at which new species are encountered as the number of observations or locations surveyed increases. Species accumulation curves provide some confidence for whether all species within a taxonomic group have been observed or whether additional species may be present but have not been detected. Throughout the report, we use species accumulation curves to assess our confidence in estimates of the total number of species found in Vermont but not to make predictions about the total number of species (Fig. 3).

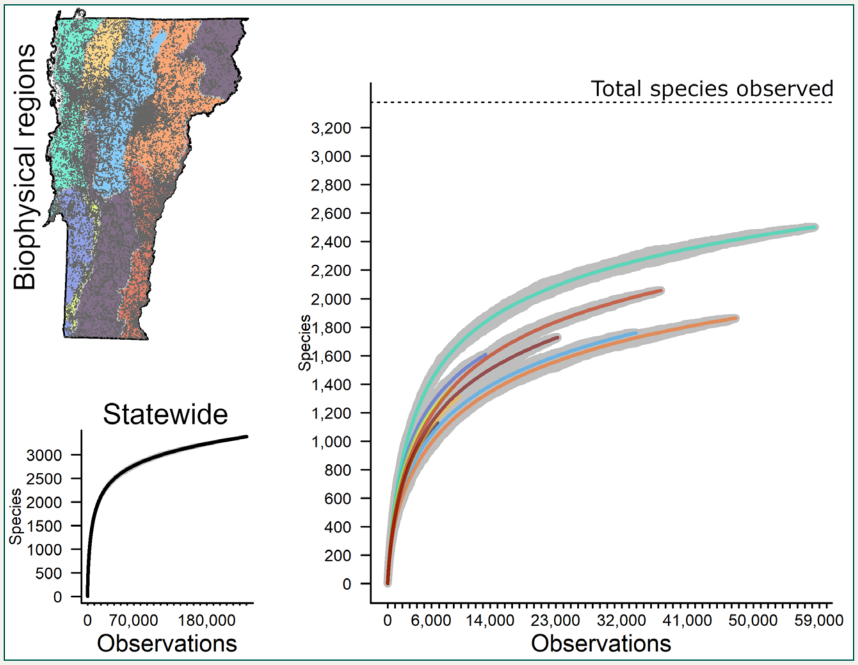


Figure 3. Species accumulation curves indicate the rate of new species encountered as a function of the number of biodiversity surveys in a particular area. Even with millions of records scattered across the state (gray dots on the biophysical regions map), we still have more to discover and document. Surveys statewide and for each biophysical region have been sampled enough to begin to flatten the curve, but total species diversity has yet to be uncovered. The species accumulation curves illustrated here are for plants.

A decade of discovering and developing primary biodiversity data

High-quality biodiversity information is vital for science and conservation. One of the most important components is *primary biodiversity data*. These are records that document the occurrence of species at a certain time and location. They may be part of a monitoring project with stringent survey methods that collect *structured data*, such as Mountain Birdwatch. They may be *semi-structured data*, opportunistically obtained through checklist surveys such as Vermont eBird or e-Butterfly. Semi-structured methods allow users to gather data wherever and whenever they wish while yielding information about the observation process, such as effort and method used. Or primary biodiversity data can be more flexible, *unstructured data* from museum collections, iNaturalist, or other sources that are often called presence-only records. These data consist of the taxonomic identification and location of an organism, often with the date of observation but without further information about abundance, sampling method, observer effort, or sites that were sampled but the species was not observed. The amount of presence-only data has grown rapidly over the past decade with the increasing popularity of community science platforms like iNaturalist, which allow users to easily submit opportunistic

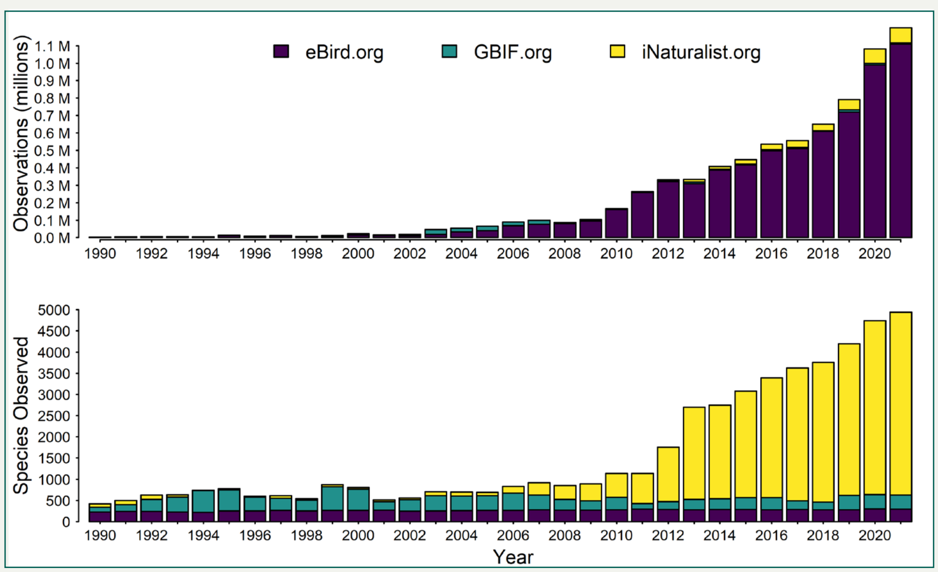


Figure 4. An annual comparison of the number of observations (top) and the number of species (bottom) to GBIF by two major crowd-source projects (Vermont eBird and iNaturalist) compared to all other records.

observations, and with the ongoing digitization of historical records and museum specimens (Fig. 4).

Structured, semi-structured, and unstructured primary occurrence data together help generate *essential biodiversity variables*, defined broadly as measures needed to study, report, and manage biodiversity change, with a focus on status and trends (Fig. 5). Essential biodiversity variables are used to help make conservation decisions at local and global scales.

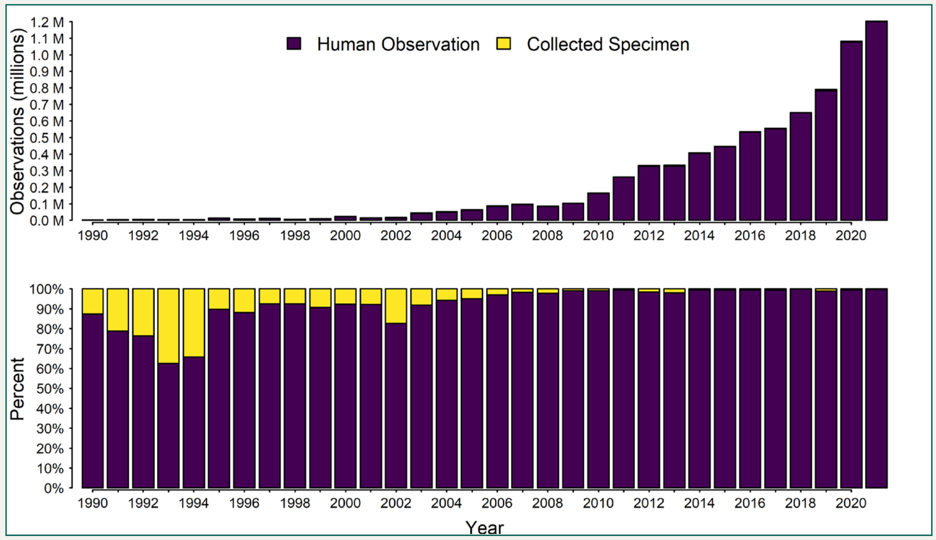


Figure 5. *The number of observations (top) and the percent that are human observations versus museum collections (bottom) reported each year to GBIF.*

Biodiversity informatics has been transformed this century by the rapid growth of community science projects and a worldwide movement to mobilize and digitize previously inaccessible data. Over the last decade, VAL has been a leader in mobilizing primary biodiversity data (Fig. 6). Our approach has been to (1) grow and support a large network of community scientists to increase the quantity and quality of biodiversity data generated in Vermont via crowd-sourced platforms and atlas projects; (2) rescue historic biodiversity records, some more than a century old, that were trapped in notebooks, print publications, file drawers, or even outdated computer files; and (3) partner with other scientists and organizations to foster data sharing. Primary biodiversity data provides the basis for many quantitative studies that can inform effective regional and global conservation decisions.

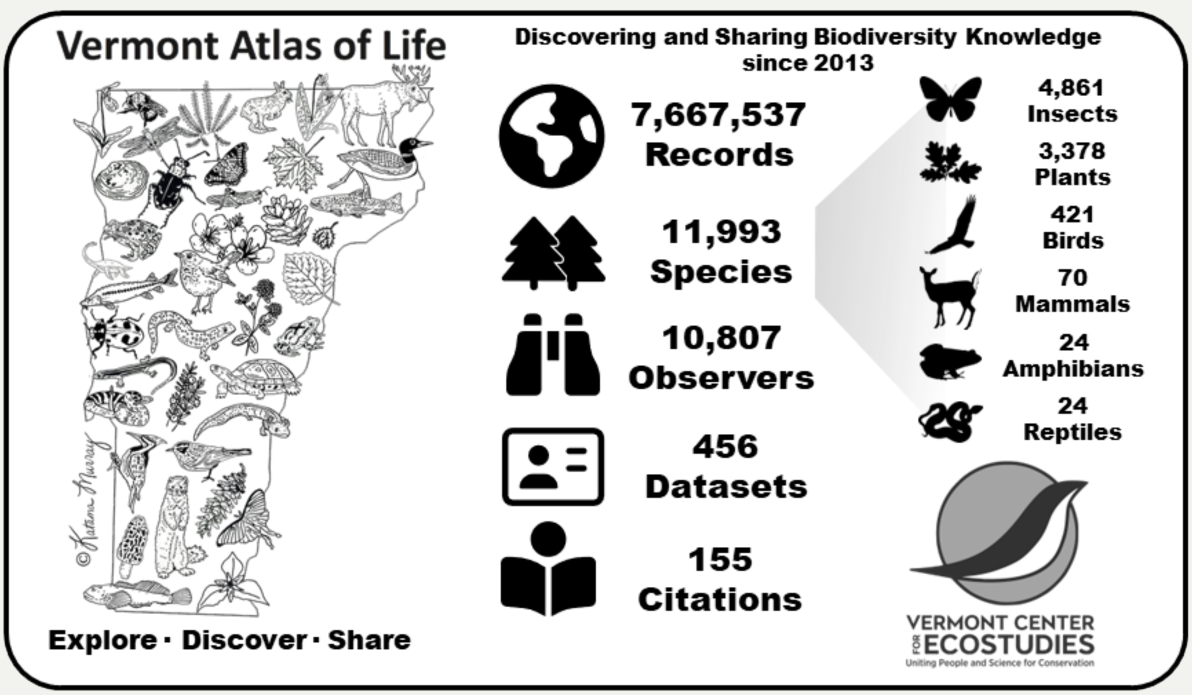


Figure 6. *A summary of all data used to generate this report. (GBIF.org downloaded 13 April, 2022, https://doi.org/10.15468/dl.j53x2g)*

Understanding Where Species Occur Today

In this report, we draw upon Vermont's primary biodiversity data to better understand how many species there are and where they occur in the state (Fig. 7). In some cases, we simply summarize the primary biodiversity data to determine what has already been observed; however, for most analyses, we couple the primary biodiversity data with climate and other environmental data to generate species distribution models. These species distribution models allow us to make inferences about what species may occur in areas of the state that are not well sampled. Species distribution models are essential for assessing conservation status and extinction risk, tracking population change, and guiding conservation efforts.

For this report, we used nearly 7.7 million primary biodiversity occurrence records shared by scientists, naturalists, and community scientists with VAL and GBIF (GBIF.org downloaded 13 April 2022, https://doi.org/10.15468/dl.j53x2g). These records, which represent nearly 12,000 taxa, form the backbone of this report. Without them, this report would not have been possible (see Fig. 6).

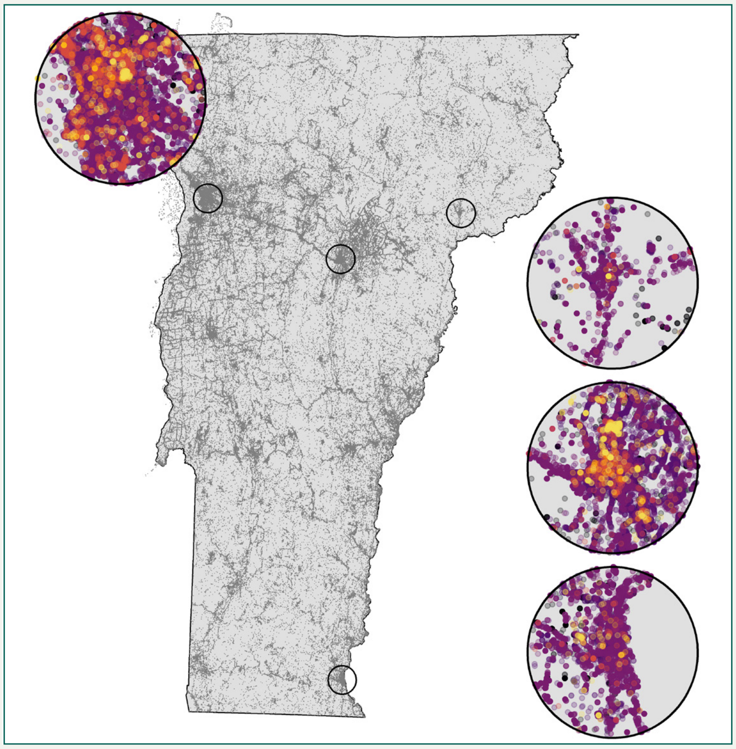


Figure 7. *Almost 8 million occurrence records have been submitted from across Vermont. The circle insets highlight observations from Brattleboro (bottom right), Montpelier (middle right), St Johnsbury (top right) and Burlington (top left). Observations in the insets are colored by taxonomic groups.*

Land cover and biodiversity records

One way we can look at the primary species occurrence data is to summarize the number of species that have been recorded in different land cover types mapped using remote sensing. We used the Copernicus Global Land Cover layers,[2] which provide 15 different classes at 100 m resolution worldwide. Although it makes up only about 10% of Vermont's land cover, open forest accounted for the highest number of occurrence records among all land cover types: 7,612 species detected in 2.4 million observations (Fig. 8). Closed deciduous forest covers the largest portion of Vermont (42%) and harbors at least 7,178 different species tallied from nearly 1.3 million occurrence records. Urban/built-up areas constitute a small fraction of the state (<10%); however, nearly 400,000 occurrence records collected since 2013 indicate that more than 5,000 species occur in these areas. Bird observations make up the vast majority (92%) of occurrence records in all land cover types, but represent just 3.5% of the species documented in this report.

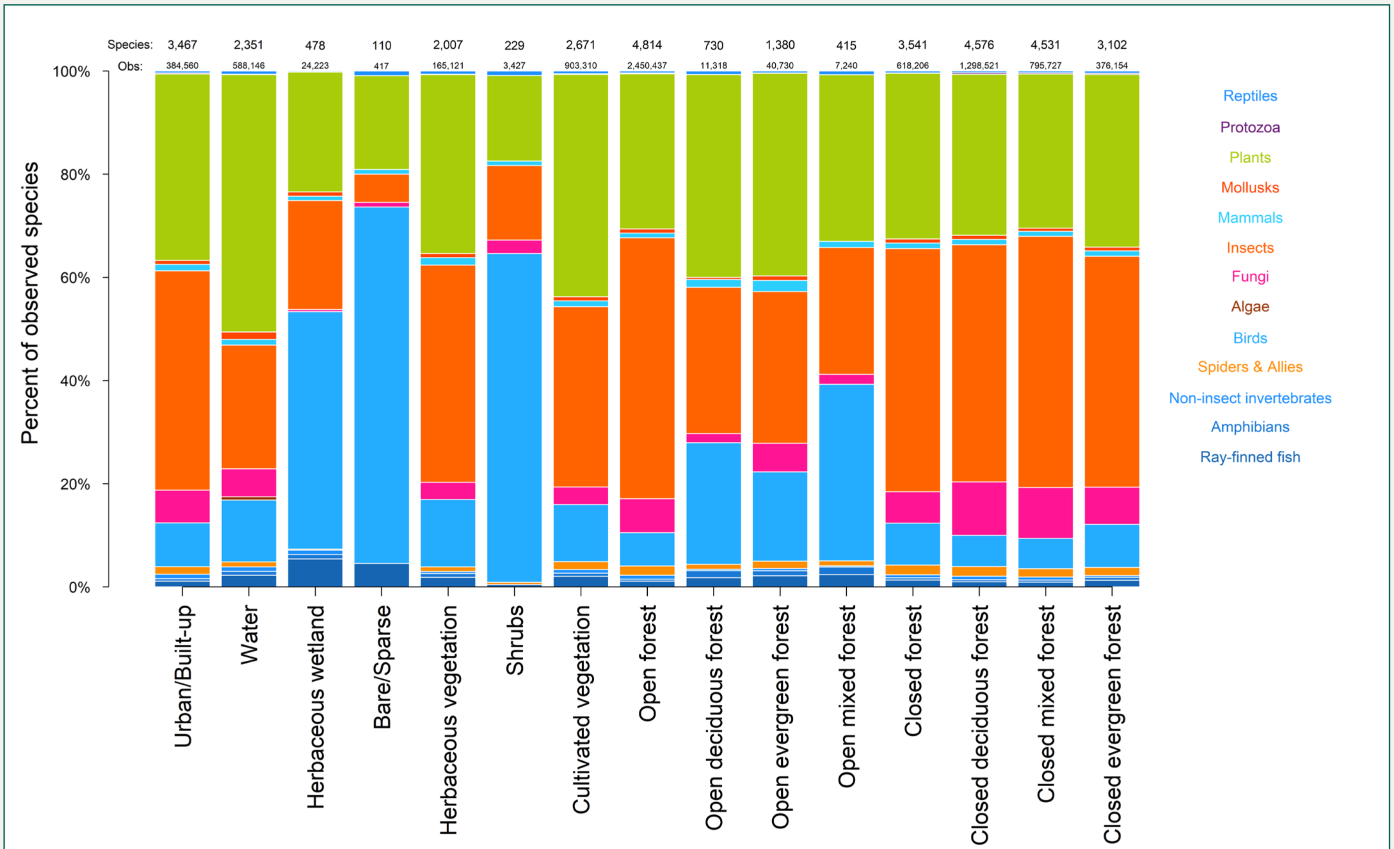
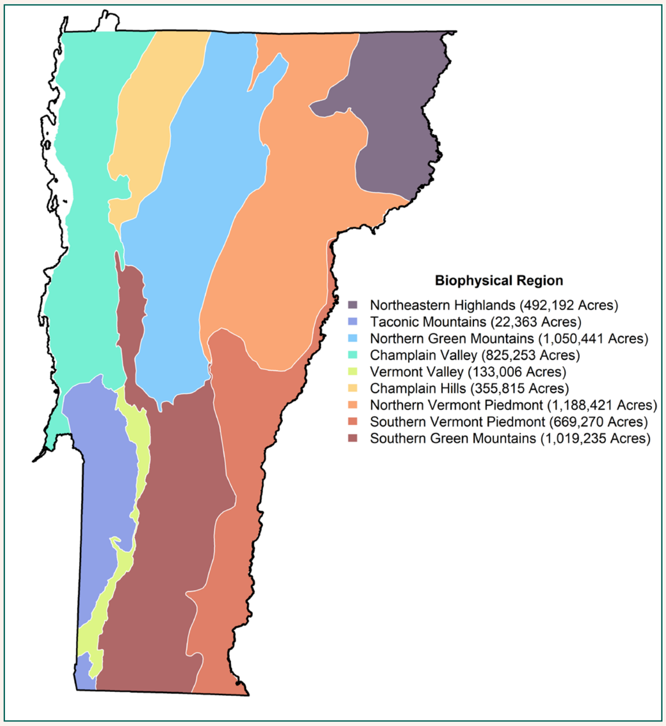


Figure 8. *The percent of observed species (by major taxonomic group) recorded for each general land cover layer in Vermont.*

Biodiversity in biophysical regions

The Champlain Valley biophysical region supported the greatest number of observed species for most taxonomic groups, including ray-finned fish (n = 96 species), amphibians (n = 21 species), non-insect invertebrates (n = 108 species), birds (n = 397 species), insects (n = 3,189 species), mollusks (n = 188 species), plants (n = 2,503 species), protozoa (n = 20) and reptiles (n = 22). The greatest mammal diversity (n = 58 species) was observed in the Southern Green Mountain biophysical region. The Northern Vermont Piedmont supported the highest observed arachnid diversity (n = 107), while observers in the Southern Vermont Piedmont observed 997 fungi species. Perhaps not surprisingly, the most observations occurred within the populous Champlain Valley biophysical region (Fig. 9). This region had the highest number of observations submitted for all taxon



Biophysical regions

Vermont has been divided into nine biophysical regions, each with a unique combination of climate, geology, topography, soils, natural communities, vegetation, and human use (Thompson & Ferree, 2008). These provide biologically meaningful boundaries to summarize biodiversity across the state. There are dramatic differences among the regions in the amount of land conserved, with the Northeast Highlands and the Northern and Southern Green Mountains containing the most by far. Each biophysical region is described in detail by Thompson et al. (2019) in A Guide to the Natural Communities of Vermont: Wetland, Woodland, Wildland.

groups except for amphibians (Southern Vermont Piedmont), arachnids (Northern Vermont Piedmont), and mammals (Northern Vermont Piedmont).

We used species accumulation curves to make direct comparisons between taxonomic groups and biophysical regions. We estimated the number of species from predictions based on our species accumulation curves at 1,000 observations. For some taxa, the anticipated number of species predicted may be greater than species known to occur in the state. For others, the predicted value will be lower than the number of species reported.

After controlling for the number of observations submitted for each taxon, the Northeastern Highlands biophysical region had the most amphibian (n = 29.9), arachnid (n = 272.4), and fungi (n = 462.9) species per 1,000 observations (Table 1). The most speciose region for insects, plants and birds was the Champlain Valley biophysical region, while the most reptiles per 1,000 observations were found in the Champlain Hills. The Southern Green Mountain and Champlain Hills biophysical regions had the most mammals and Mollusca species, respectively.

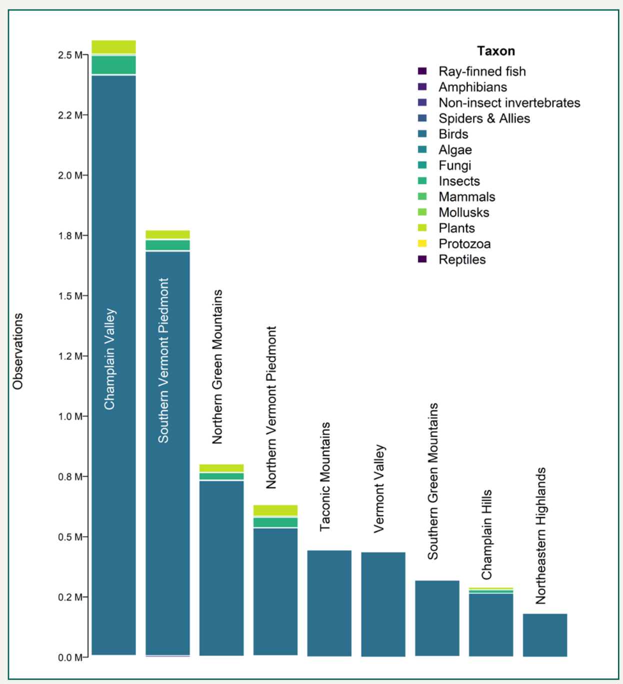


***Figure 9**. The number of observations by major taxonomic group reported in each biophysical region.*

	Biophysical Region								
Taxon Group	Northeastern Highlands	Taconic Mountains	Northern Green Mountains	Champlain Valley	Vermont Valley	Champlain Hills	Northern Vermont Piedmont	Southern Vermont Piedmont	Southern Green Mountains
Amphibians	29	21	18	19	22	21	17	16	19
Birds	138	161	145	223	151	151	161	188	140
Fungi	462	379	393	381	412	373	310	454	430
Insects	332	281	481	581	358	390	514	531	306
Mammals	46	53	47	36	59	50	34	43	61
Mollusks	242	261	224	216	349	148	112	177	276
Plants	428	487	448	661	459	414	449	505	450
Reptiles	5	31	16	19	23	25	9	12	22
Spiders and allies	272	198	128	124	196	122	96	112	127

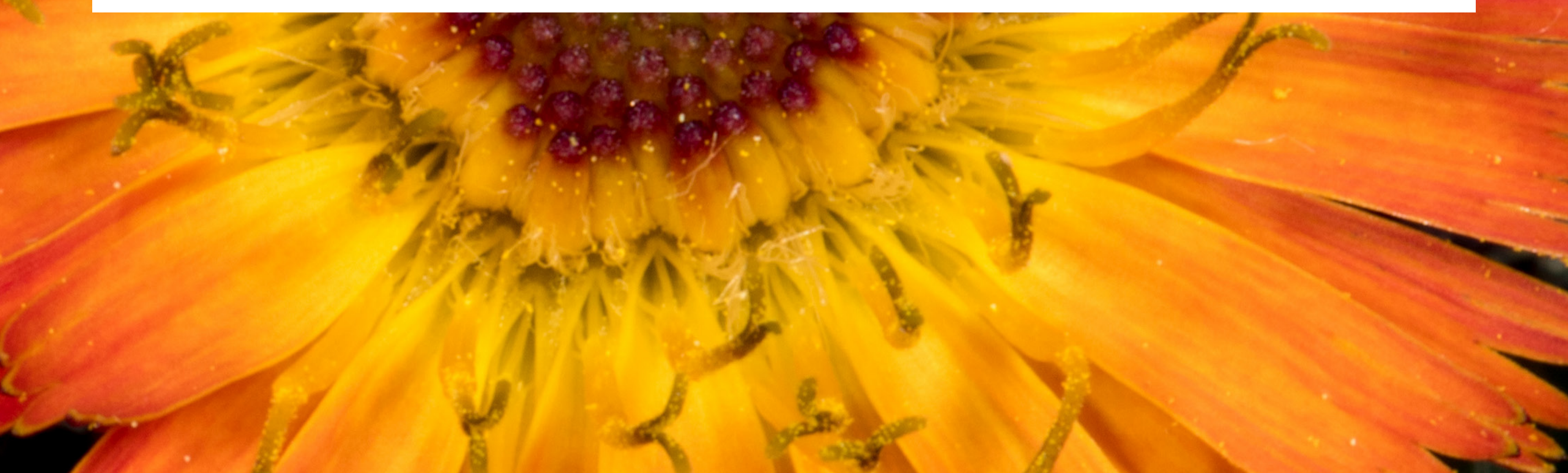
Table 1. The number of expected species given 1,000 observations. Please note that we rounded down when species number was a decimal (i.e. 29.9 amphibians became 29).

Biodiversity across public and private lands

The majority of Vermont lands are privately owned. Just one-quarter of Vermont is defined as conserved land, with nonprofit organizations owning 35.4%, federal and state governments each holding about 30.5%, town governments 3.6%, 0.01% tribal, and a small fraction with unknown ownership (0.02%).[3] About 76% of Vermont is forested, of which 20% is publicly owned, 19% is controlled by corporations and other entities, and the remaining 61% is held by private landowners.[4] A majority of private forest landowners in Vermont own fewer than 50 acres.[5]

Understanding how biodiversity is distributed across the complex matrix of private and public lands in Vermont is needed to assess whether conserved lands adequately conserve species. With the ratio of land ownership highly skewed towards private holdings without conservation easements, identifying where primary biodiversity data are recorded can help us to adequately monitor and manage biodiversity across the mix of private and public lands in Vermont.

Conservation lands can be managed for purposes other than biodiversity conservation. The U.S. Geological Survey (USGS) Gap Analysis Project (GAP) created a metric called the GAP status which is a measure of management intent to conserve biodiversity.[6] The metric has four levels and ranges from GAP status 1 to GAP status 4 based on the management plans for the parcel. Parcels with a GAP status of 1 or 2 are generally conserved for biodiversity since the management on these lands is minimal or intended to maintain their natural state. Conserved lands that fall into GAP status 3 also favor biodiversity conservation but their management plans allow either low-intensity use over large areas or intensive use in smaller areas. Parcels with GAP status level 4 have no mandates to prevent conversion of habitat from a natural state to a non-natural state. These have a lower conservation value for biodiversity because of the potential for development or alteration (Fig. 10).



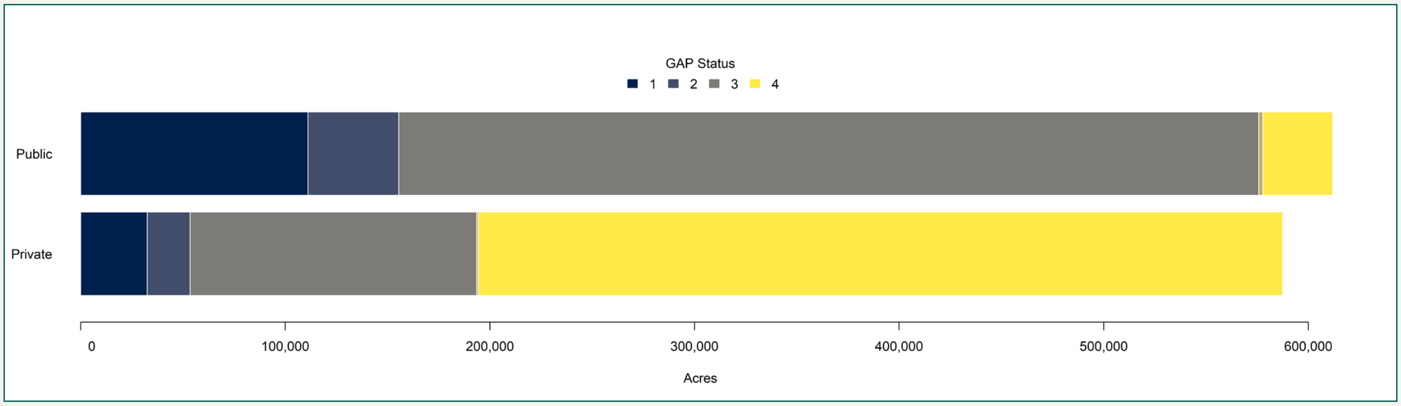


***Figure 10**. Public versus private conservation lands GAP status.*

We summarized VAL's primary biodiversity data submitted from conservation lands to assess where species are being observed. We summarized observational data by land ownership type (public or private) and GAP status class to identify potential biases in where species are being observed across Vermont.

More species in all taxonomic groups have been observed on private lands conserved for the benefit of biodiversity than their public conservation land counterparts, but this difference is especially pronounced for arthropods (Privately owned: 1,229 species; Publicly owned: 789 species). In contrast, more species of all taxonomic groups except for birds have been observed on public conservation lands that fall into GAP status 3, perhaps because the acreage of public conservation lands with GAP status 3 (public acres: 420,247; parcels: 2,072) is nearly triple the acreage of private lands in the same category (private acres: 140,083; parcels: 863). Greater access to public lands, in general, helps explain why more observations originate from public lands than from private lands. For some taxa, such as amphibians, there are more than three times as many observations submitted from public (n = 4,987) than private lands (n = 1,328). Nonetheless, private lands had more unique species on average than public lands (Fig. 11). Since much of Vermont is privately owned, private lands are and will continue to be key to supporting biodiversity conservation into the future.

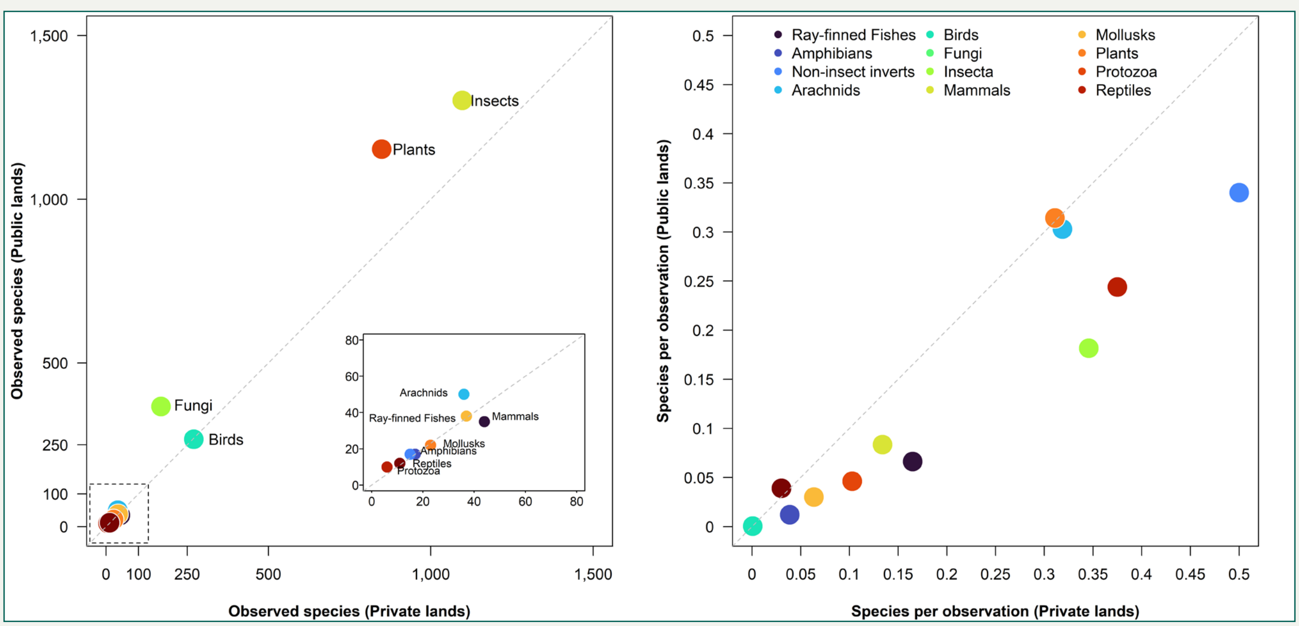


***Figure 11.** Species on public versus private conservation lands.*

Predictive species distribution models

To conserve species, we have to know where they occur. For centuries, amateur and professional scientists have scoured the planet, discovering and mapping biodiversity. In spite of these efforts, the complete distribution of most species is still poorly known. We cannot possibly cover the entire landscape, even here in Vermont. Recent statistical and computational advances now allow us to use relatively few primary biodiversity occurrences for a species to predict their range using sophisticated species distribution models (SDMs).

We used a machine-learning technique called maximum entropy modeling (Maxent) to quantify associations between each species' occurrence records and physical attributes (soil pH, parent bedrock, and underlying soil characteristics) and bioclimatic variables (temperature, precipitation, and other climatic characteristics) that may play a role in determining where species occur.[7] Because we used a combination of contemporary and historical occurrence records for species, we did not include land use in these models as it can undergo dramatic change in relatively short periods of time. We used species occurrence records that were recorded with a location accuracy of <0.25 miles (<400 m) to create presence-only grids with 0.62 x 0.62 miles (1 x 1 km) cells that match the environmental attribute grids. The Maxent model results in a probability distribution where each grid cell has a predicted suitability of conditions for the species. The habitat suitability maps were converted into a binary surface indicating whether a species was likely present or likely absent based on the underlying predicted suitability. These species distribution models were used as the basis for additional analyses throughout the report. The resulting maps from the species distribution models are available on individual species account pages or via request.

We supplemented the Vermont species occurrence records with more than 114 million records comprising 46,164 taxa from across the Northeast (GBIF.org downloaded 13 April 2022, https://doi.org/10.15468/dl.j53x2g) to better predict where species may occur within Vermont. We did this to (1) increase the number of occurrences for individual species that are known to occur within the state but may only have a few Vermont observations; (2) include those that may be found in the state but only have records reported from nearby; and (3) those species that may have ranges that currently do not reach Vermont, but could in the future with climate change.

There was sufficient data to model distributions for 7,211 species, which represent most of the major taxonomic groups found in the state (Fig. 12).

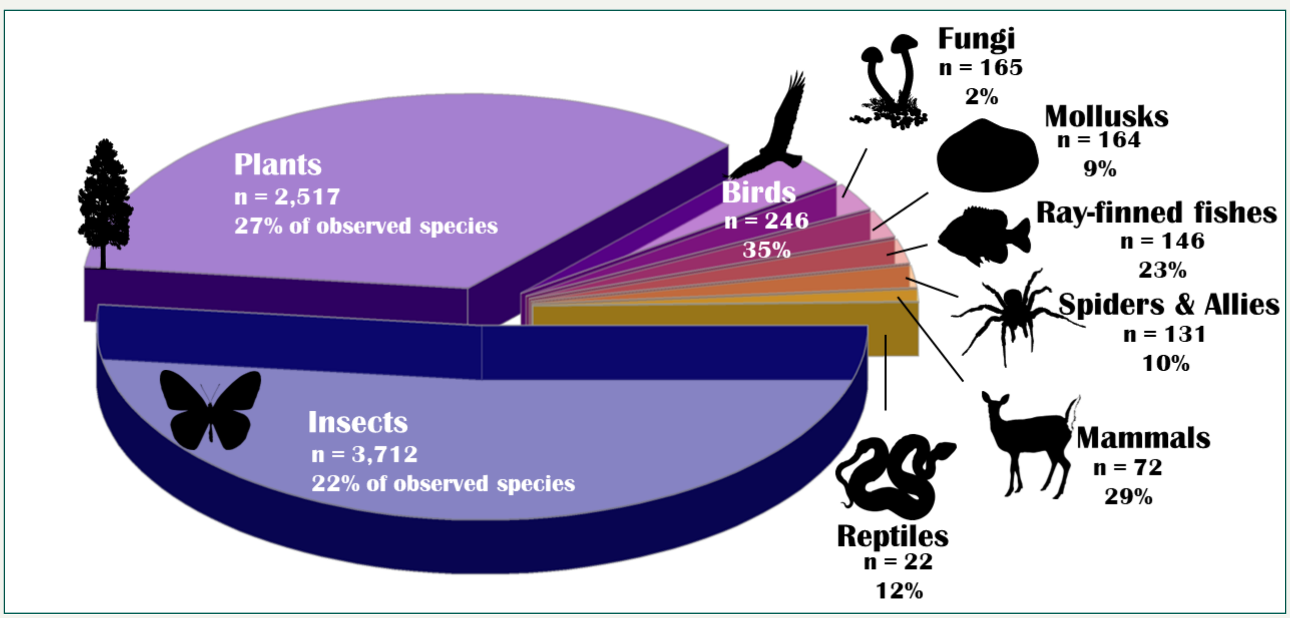


Figure 12. There was sufficient data to create Species Distribution Models for 7,211 species, which represent most of the major taxonomic groups found in the state. The number of species in each major taxonomic group is shown. The percentage of species with species distribution models from the regional species found throughout New England is also presented.

Of the modeled species, mammals are the group with the largest median distributions in the state (10,924 km²), followed by insects (5,013 km²), birds (2,521 km²), plants (2,387 km²) and reptiles (264 km²; Fig. 13).

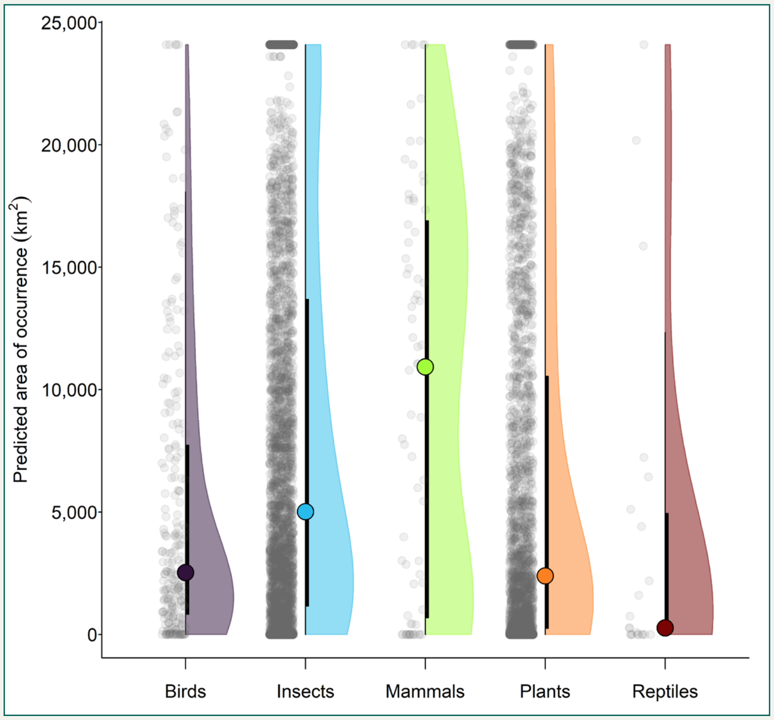
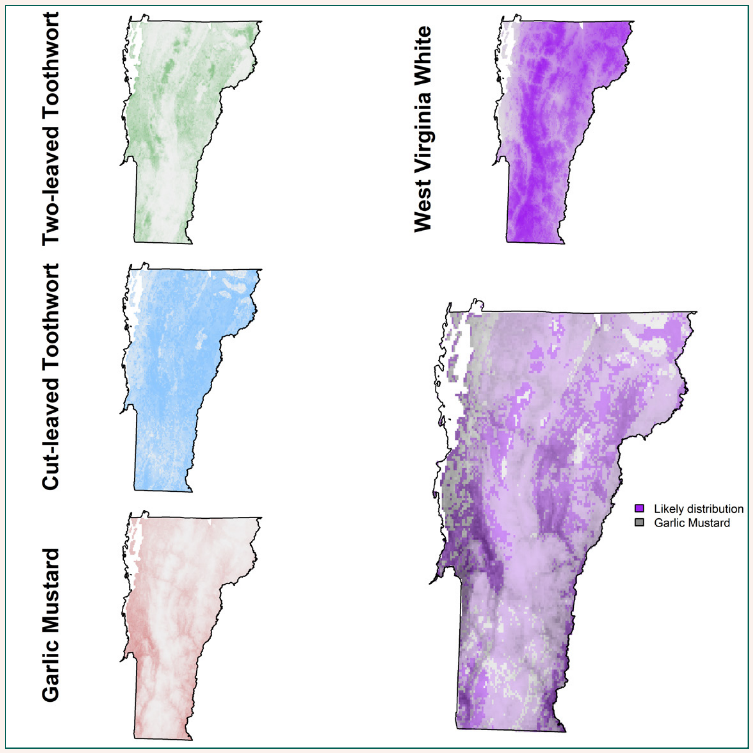


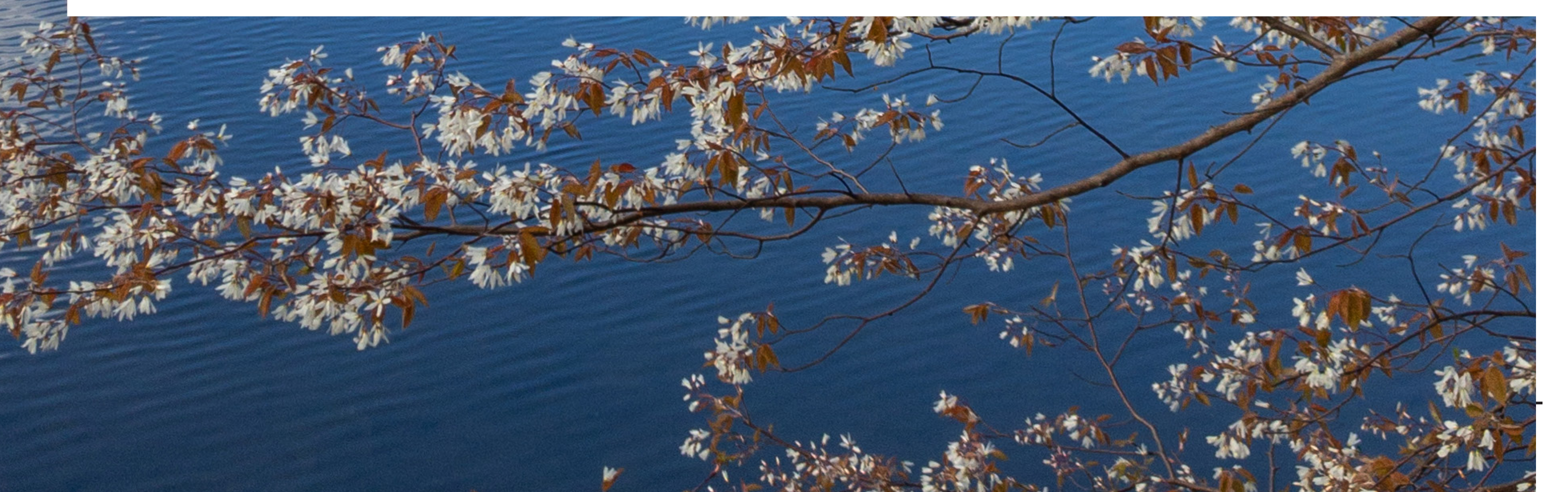
Figure 13. *We summarized the area of predicted occurrence using Species Distribution Models. The gray dots to the left of the distribution show individual species. The large points represent the median value and the thin solid black lines represent the interquartile range while the larger black lines represent the 95% confidence interval.*

Case Study: West Virginia White Butterfly



It's not a gaudy butterfly. It isn't the biggest or the smallest. In fact, it's mostly just white. But this butterfly is unusual; it only flies in intact forests. It's an ephemeral spring wildflower groupie. To see this butterfly you need to visit rich, mature hardwoods with spring wildflowers before the trees leaf out. Follow a woodland stream until you find the host plant—and the butterfly. Their flight is slow and close to the ground.

Its caterpillars only feed on a few plants, mainly Crinkleroot (*Cardamine diphylla*) and Cut-leaved Toothwort (*Cardamine concatenat*a). But there's a dirty player in the field—introduced Garlic Mustard (*Alliaria petiolata*). First found in the United States in 1868, this invasive plant has encroached on toothwort and caused local extirpations of native plants. And even though chemicals in Garlic Mustard appear to be toxic to West Virginia White (*Pieris virginiensis*) caterpillars, adults are attracted to it and lay eggs on it. As a result, West Virginia Whites are at risk and classified as a species of special concern in Vermont.



Important factors affecting species distributions

Our species distribution models generate variable importance scores, which provide insight into the most important predictors of species occurrence. For example, high variable importance scores for attributes associated with temperature suggest those species distributions may be more impacted by temperature than either precipitation or physical attributes of the landscape. Across all taxa, the mean importance score was greatest for physical attributes (37%), followed by precipitation (29%), and finally, temperature (25%). For most taxonomic groups, physical attributes of the landscape were an important determinant of their occurrence. Bioclimatic variables representing precipitation were more important than temperature for most taxonomic groups (Fig. 14). While climate change is affecting temperatures across the Northeast, the amount of precipitation has changed since the early 1900s and is predicted to change considerably in the future, particularly during the winter months. These changes in precipitation will likely have an impact on many taxa currently found in Vermont.

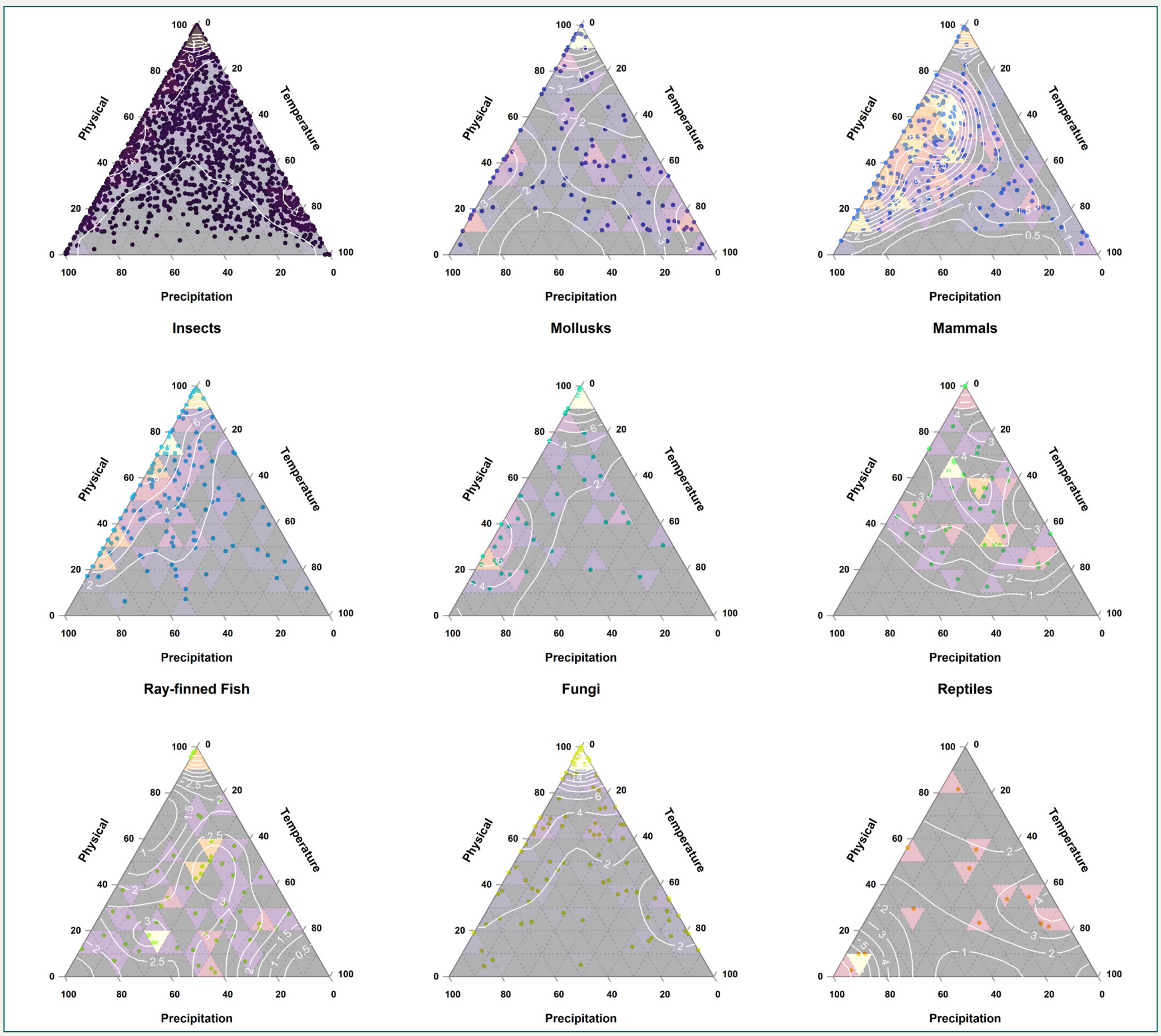


***Figure 14**. Ternary plot showing the relative importance of precipitation, temperature and physical landscape variables shaping species distributions. The median value for each genus is represented by the points and the underlying color ramp (purple = low, yellow = high) represents the density of the genus-level responses. Each plot represents a taxonomic group of organisms.*

We used the species distribution model results to identify areas in the state that support the greatest species diversity. A few areas are predicted to have over 3,500 species, and that's almost certainly an underestimate of the true species richness since only a subset of the species had the data requirements to model distributions. These areas occur primarily within the Champlain Valley biophysical region (Fig. 15). Other biodiversity hotspots include areas along the Connecticut River in southeastern Vermont.

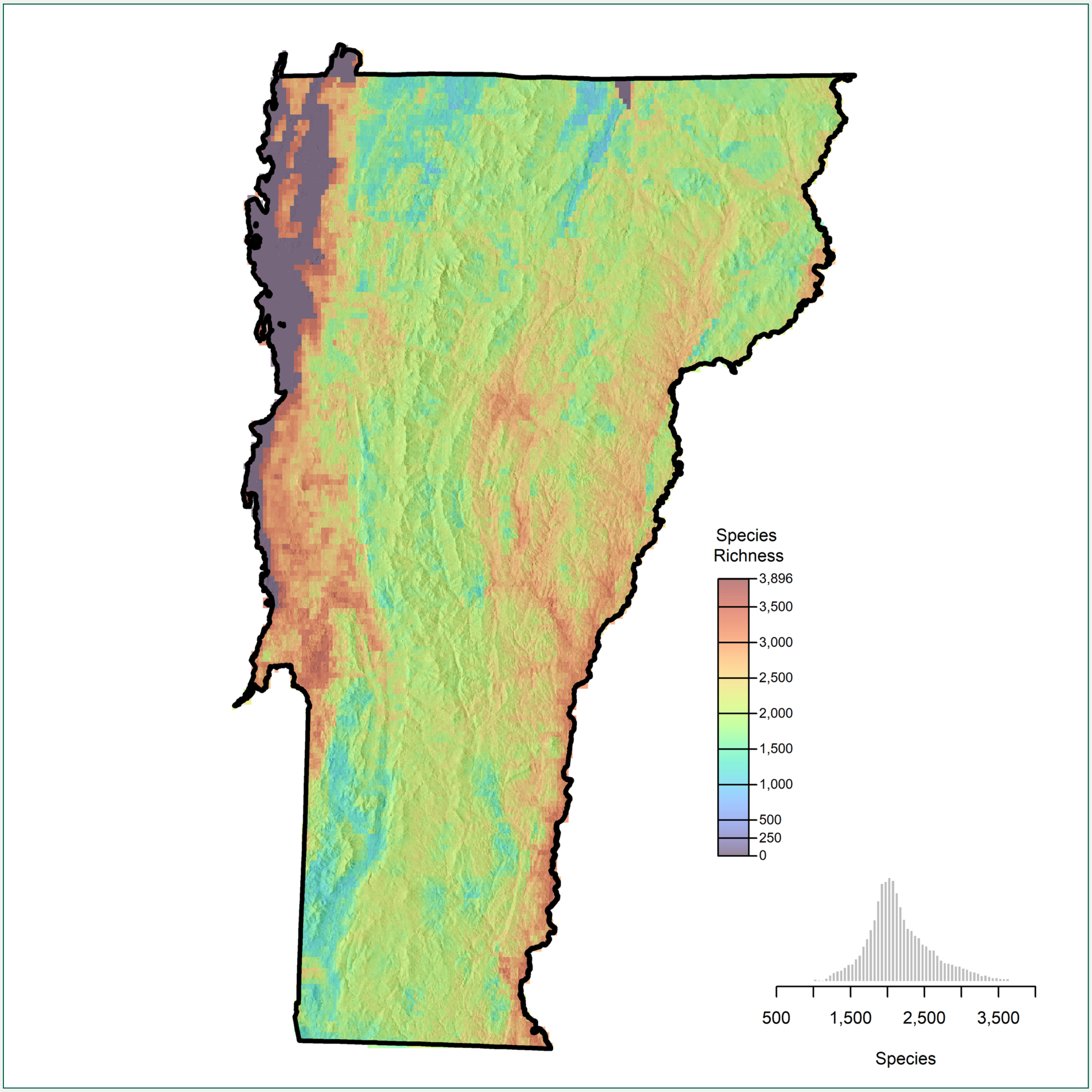


Figure 15. *A map of the predicted species richness derived from Species Distribution Models predictions for each area (0.62 x 0.62 miles; 1 x 1 km) of Vermont.*

Species distribution models allow us to see the Vermont landscape in new ways. For example, we can use these data to identify potential biodiversity hotspots and summarize the data in various ways to answer new questions. The species distribution models can also be used to create checklists for towns, inform the work of conservation commissions, enable researchers to select field sites, and guide work on future atlases. Perhaps more importantly, these data can be used to assess conservation design and help future decision-making.

Conserved lands and the species they protect

We used the species distribution models to ascertain the proportion of a species range that falls within currently protected areas. These estimates can identify species that may require further protection. We included both public and privately owned conservation areas with a GAP status of 1 or 2. Combined, Vermont's public and private lands managed for a natural or primarily natural state encompass just over 13% of species distributions on average, or approximately 187,684 acres (80,000 hectares; Fig. 16).

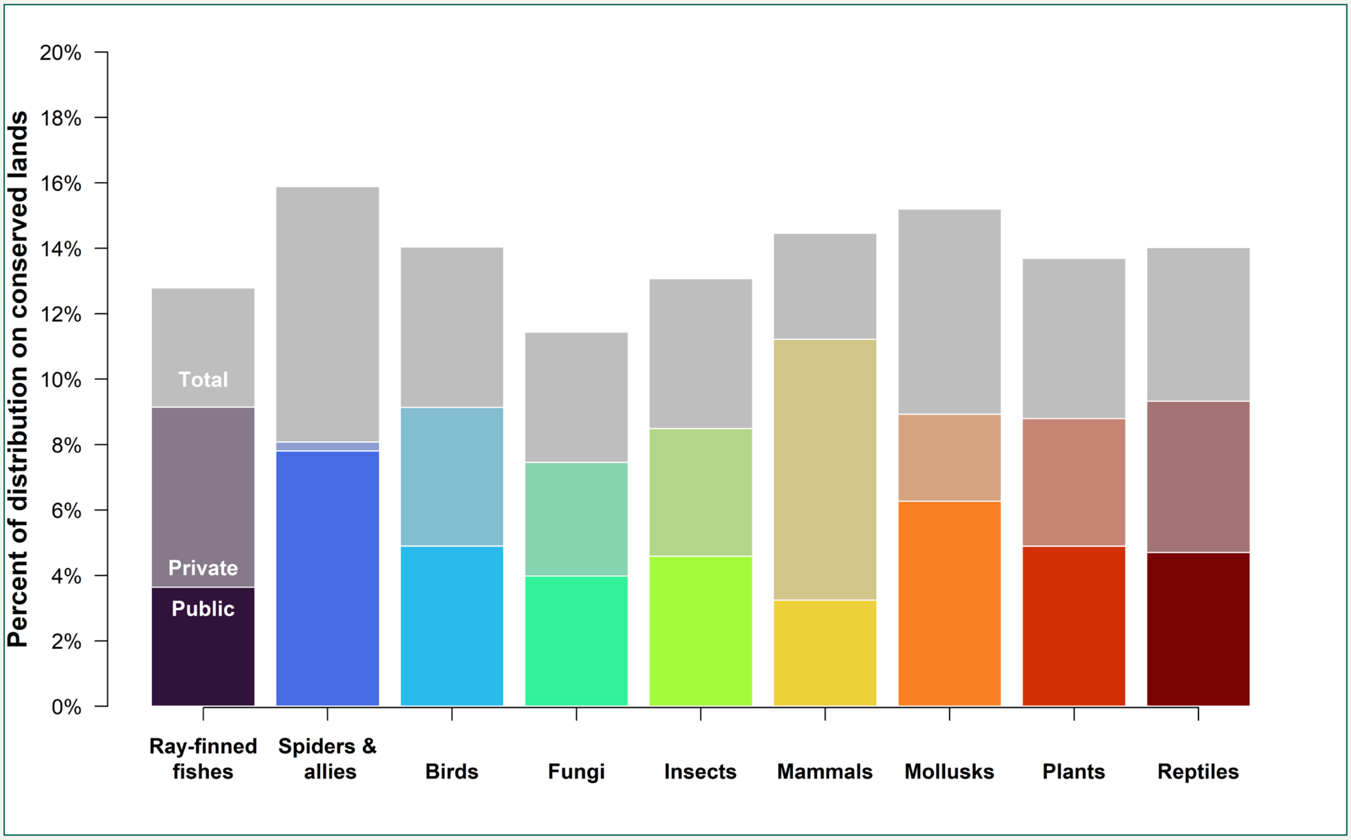


***Figure 16**. The percentage of species distributions that occur within private conservation lands is larger than public conservation lands. The gray bars show the total percent of species distributions that occur within conserved areas - dark colors represent the proportion of distributions that occur within public conserved lands (%), lighter colors show the proportion of distributions that occur within privately owned conservation lands. The sum of the two colored bars equates to the total percentage of individual distributions that occur within conserved lands (gray bars). This allows for direct comparison between private and public conservation lands. In all cases, the percentage of distributions within private conservation lands is larger than public conservation lands.*

Private conservation lands play an important role in protecting Vermont's biodiversity. Those set aside for biodiversity conservation contain a larger percentage of species distributions across all taxonomic groups than publicly-owned conservation lands on average. According to our models, spiders and allies have the largest percentage of distributions found in protected areas (15.9%), while fungi have the lowest level of protection at the species level (11.4%; Fig. 16).

Predicting and mapping unique communities

Areas that harbor unique communities are critical for maintaining biodiversity in the state. Beta diversity can be used to quantify the uniqueness of communities within a region and assess the potential conservation value of a location for maintaining biodiversity. To calculate beta diversity, a complete sampling of the community is needed. Conventionally, this requires hours of field observation and various sampling techniques to count and identify all or most of the species within a few study sites. While informative, that approach is limited by the number of sites that can be sampled. We used the predictions from our species distribution modeling to assess biological communities across the state. We calculated community uniqueness for every taxonomic class that had three or more species with distribution models. We determined where unique communities exist within Vermont by calculating a location's (0.62 x 0.62 miles; 1 x 1 km) local contribution to the state's beta diversity.[8] Areas within the 95th percentile were deemed locations that harbor unique communities for each Class of organisms (Fig. 17). We then calculated the percentage of the land area where unique communities occur that is currently protected or in some form of conservation easement.

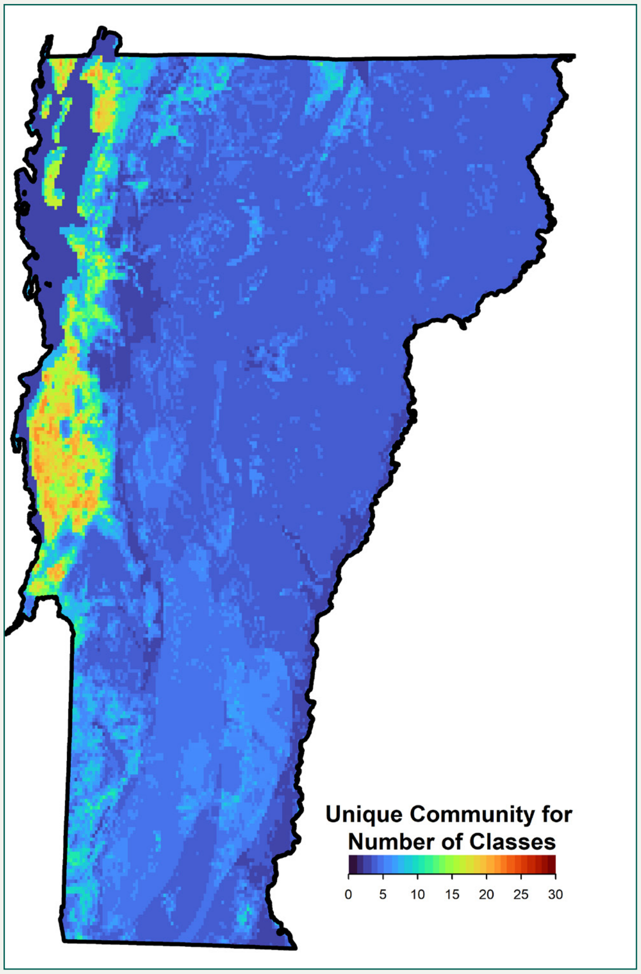


Figure 17. We used the predictions from our species distribution modeling to assess biological communities across the state. We calculated community uniqueness for every taxonomic class that had three or more species with distribution models (n = 30). The map highlights locations identified as unique communities for multiple classes.

Limitations

The findings presented throughout this report are a step forward for biodiversity conservation within Vermont. However, there are several limitations associated with the data and the various models presented in the report. For example, much of the data submitted to VAL are opportunistic observations, meaning most observations provide information about where species are present, with little data on where they are absent. Opportunistic observations occur in areas where people frequent, and thus fewer observations occur in remote areas of the state. We did our best to account for observational biases, but many still exist.

Species distribution models built from occurrence records allow us to make predictions about species in locations with few or no observations and also in remote regions of the state. Species distribution models perform well with many species-specific observations from across the region and when parameterized with biologically relevant variables. Here, we modeled species distributions using the same set of variables for all species, mainly bioclimatic factors, because it would have been impossible to tailor the factors affecting each of the 14,000+ species we attempted to derive species distribution models. The species distribution models we present in this report are predictions but derived from the most complete data we have access to. These predictions have a spatial resolution of 0.62 x 0.62 miles (1 x 1 km) and are suitable for statewide analyses but are generally too coarse to make parcel-level assessments. While some species may be predicted to occur within one of the cells (1 x 1 km) based on the bioclimatic variables, they may only occur within the appropriate habitats in that block or perhaps not at all if the habitat is not present.

In addition to data and modeling limitations, taxonomic limitations also exist. The number of trained taxonomists is declining and there is a lack of trained individuals who are qualified to identify observations. Furthermore, many species can't be identified from photographic evidence. Not having enough trained taxonomists limits the scope of species that could be included in this report. Some species require specimens to be identified and therefore only museum collections could be used in some analyses.

Conservation Status of Vermont's Flora and Fauna

Ranking species according to their risk of extinction is an important exercise that helps to prioritize which species most urgently require conservation action to prevent extinction. Several ranking systems are used in Vermont. Some consider species status at a statewide scale, while others consider the global status of species. Scientists at the Vermont Center for Ecostudies are often involved in conducting these detailed species status assessments. For many species, VAL holds the best, and often only, data available to help make status recommendations.

The Red List of Threatened Species

The International Union for Conservation of Nature (IUCN) was founded in 1948 as the world's first global environmental organization. A major aspect of their work is assessing the conservation status of different species and assigning rankings to help prioritize conservation actions. The IUCN Species Survival Commission manages this work, and the rankings are published in the IUCN Red List of Threatened Species, an internationally recognized system for evaluating conservation status. The list aims to help prioritize the species that most urgently need conserving and provide a global biodiversity index. The process of assigning rankings is very thorough and based on scientific evidence. Thousands of scientists around the world, including VAL scientists, are involved in IUCN rankings.

Several species that have been recorded in Vermont are either critically endangered (n = 7) or endangered globally (n = 15). Nearly 80 other species are ranked either near threatened (n = 37) or vulnerable (n = 37) by the IUCN (Fig. 18). The vast majority of insect species either have not yet been evaluated by the IUCN or fall into the data-deficient rank, indicating that there are not enough data for those species to be assigned a global rank. Most species that occur in Vermont have a global rank of Least Concern; however, some species of Least Concern globally are relatively rare or declining in our region.

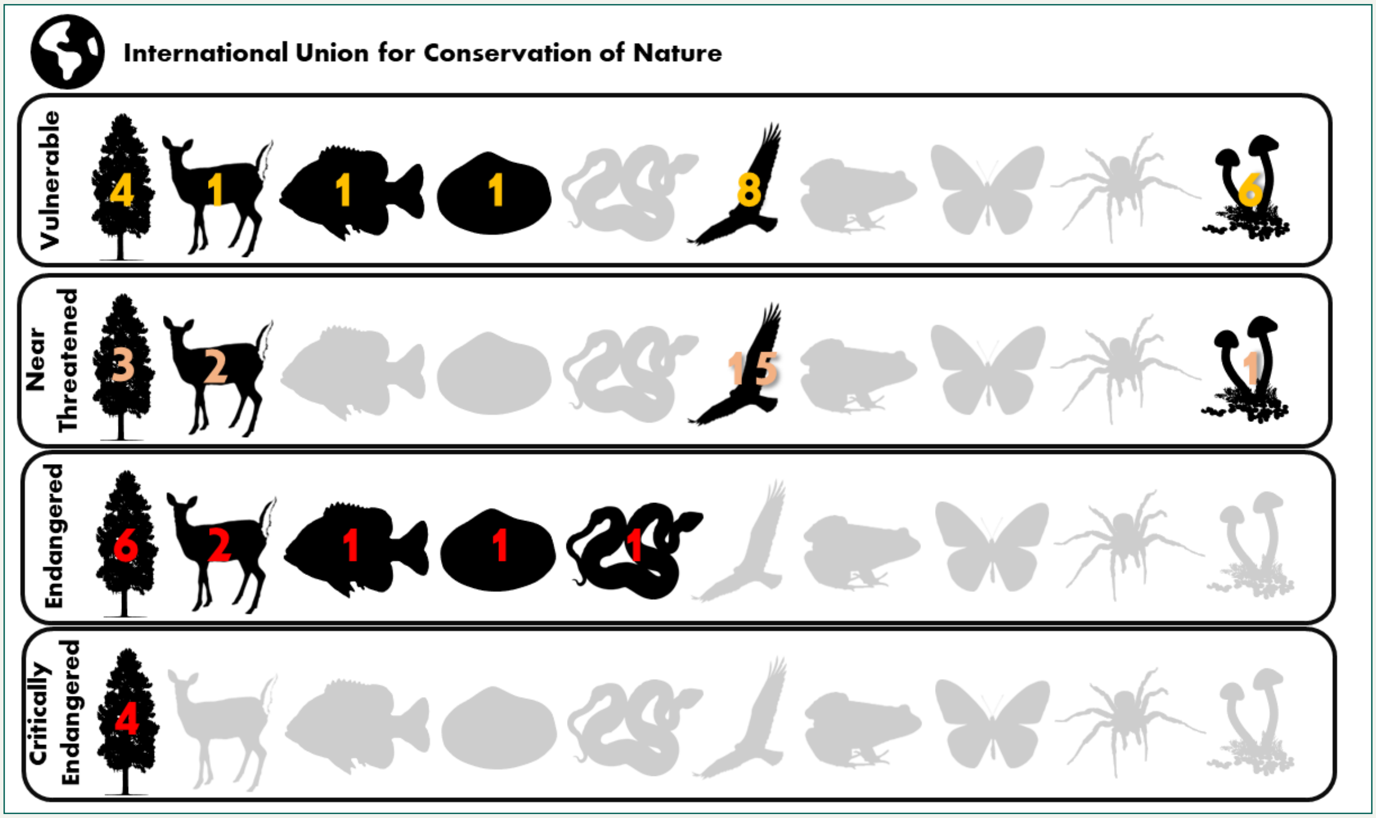


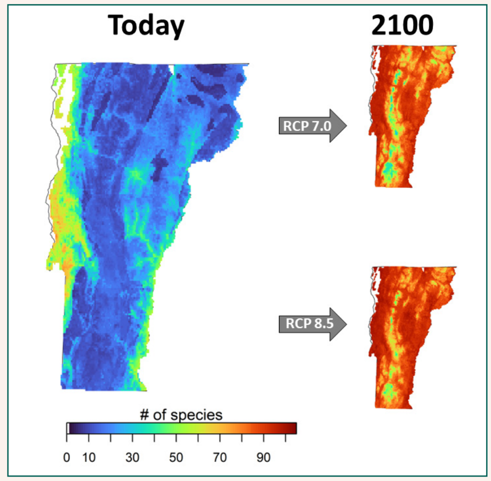
Figure 18. *The number of species in Vermont for each International Union for the Conservation of Nature (IUCN) conservation rankings.*

NatureServe Conservation Status Ranks

NatureServe conservation status ranks are part of an international ranking system first developed by The Nature Conservancy and now managed by NatureServe. This system is used by Natural Heritage programs in all 50 states, by the 8 Canadian Conservation Data Centres, and by other international partners. NatureServe, Network Programs, and collaborators like VAL use a rigorous, consistent, and transparent methodology to assess the conservation status (extinction or extirpation risk) of species. The Vermont Natural Heritage Inventory, part of the Wildlife Diversity Program at the Vermont Fish and Wildlife Department, gathers data and assigns Conservation Status Ranks (S-ranks) at the subnational or state level in cooperation with partners like VAL. Assigning a Conservation Status Rank to a species requires scoring it along 10 conservation status factors, then weighting and pooling the scores into an overall score, which is then translated into a calculated rank, ranging from S1 (very rare/critically imperiled in the state) to S5 (common and widespread/secure). To learn more about NatureServe ranking, visit NatureServe Conservation Status Assessments: Methodology for Assigning Ranks.

Assigning S-ranks to species requires a considerable amount of primary biodiversity data. Sufficient data are available to assign S-ranks to 3,390 species in Vermont, mostly plants, reptiles, amphibians, and birds; however, some species—even entire taxonomic groups—currently lack Vermont S-ranks due to data deficiencies (Fig. 19). By crowdsourcing and vetting primary biodiversity data, VAL is helping to solve this dilemma for invertebrates and other under-surveyed groups.

Invasive Species



The recent proliferation of invasive species that outcompete, parasitize, or prey on native species has become a widespread threat in Vermont and beyond. Invasives are non-native species to an ecosystem and when introduced cause environmental and economic harm, and in some cases affect human health too.

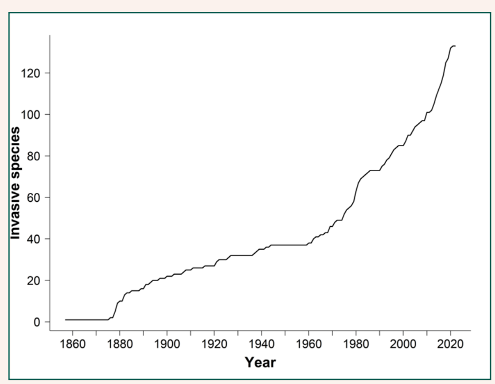
The Nature Conservancy reports that invasive species have contributed directly to the decline of 42% of the threatened and endangered species in the United States. NatureServe (2023) found that invasive species and diseases threaten many imperiled plants (63%), and both terrestrial (53%), and freshwater animals (42%).

Invasive species are introduced via many pathways, including hitching a ride on transportation systems, well-meaning wildlife plantings, or introductions from agricultural and horticultural operations. For example, about 85% of the woody invasive plants originally established from ornamental plantings (Reicherd and White 2001).

The U.S. Fish and Wildlife Service reports that invasive species cost the nation more than $120 billion in damages annually, with more than 100 million acres affected by invasive plant infestations. A recent economic analysis found that annual invasion costs increased from $2 billion during the 1960s to $21 billion in 2010 to 2020 (Fantle-Lepczyk et al. 2022). The total cost estimate for the Northeast alone was $630 million.

The most cost and environmentally effective approach to controlling invasive species is prevention or early detection and management. As time passes, invasive species are more costly and more difficult to remove, and management options narrow. With thousands of participants reporting observations to our crowd-sourced projects, VAL is in a unique position to help with early detection and future predictions.

Since the inception of VAL a decade ago, 31 new invasive species have been detected in Vermont. There are now more than 11,000 observations from well over 100 invasive species have been observed at least once. Seven invasive species have over 500 observations in VAL. Of those species, 85% are established plant populations. The Spongy Moth (*Lymantria dispar dispar*) is the only non-avian animal with over 500 observations in VAL. European Buckthorn (*Rhamnus cathartica*; n = 1,172), Purple Loosestrife (*Lythrum salicaria*, n = 942) and Garlic Mustard (*Alliaria petiolata*, n = 824) are the invasive species with the most observations. These species have been in Vermont for over a century with their first observations in GBIF dating back to 1882,1885, and 1907, respectively. The Spotted Lanternfly (*Lycorma delicatula*), an agricultural pest native to Asia and first detected in Pennsylvania in 2014 is the newest invasive species observed in Vermont, but has not yet established any reproducing populations. While the Spotted Lanternfly is not established in Vermont, early detection of individuals and egg masses will help prevent its spread when they arrive inadvertently. Community scientists and VAL are and will continue to play an important role in the early detection of harmful invasive species across Vermont.



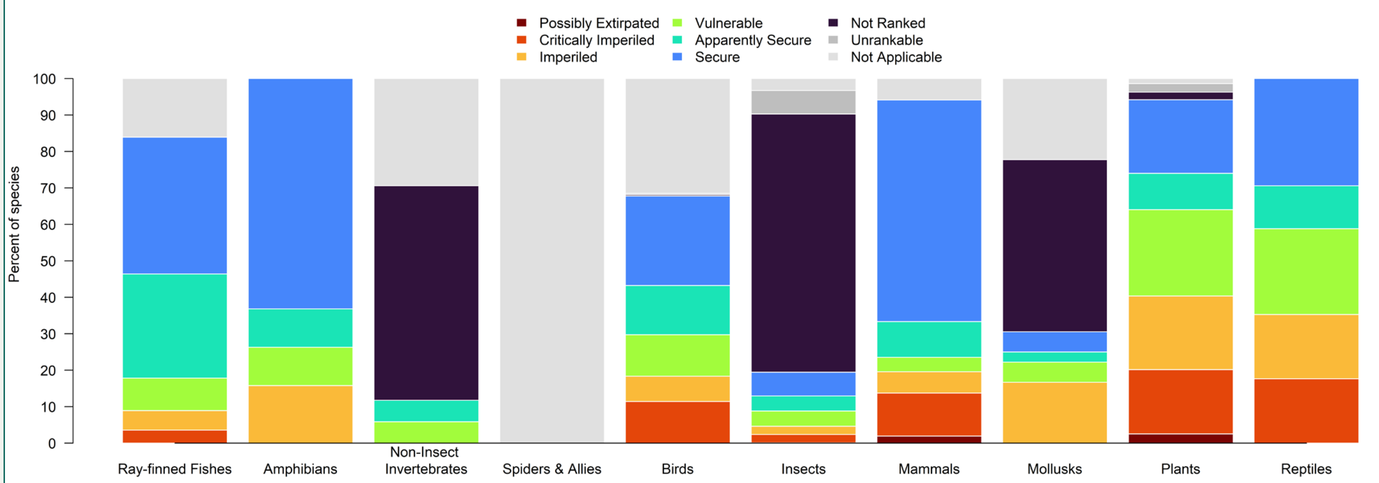


Figure 19. *The Vermont Natural Heritage Inventory, part of the Wildlife Diversity Program at the Vermont Fish and Wildlife Department, gathers data and assigns Conservation Status Ranks (S-ranks) at the subnational or state level in cooperation with partners like VAL. Assigning S-ranks to species requires a considerable amount of primary biodiversity data. Sufficient data are available to assign S-ranks to 3,390 species in Vermont. The bar chart shows percent of species for each taxonomic group according to the current rankings.*

Species of Greatest Conservation Need

Congress created the State and Tribal Wildlife Grants Program (SWG) in 2001. To receive SWG funds, each entity is required to develop a Wildlife Action Plan (WAP). The first Vermont WAP was completed in 2005. The goal of both the State Wildlife Grants program and the Action Plan is to prevent wildlife from becoming endangered through early, strategic efforts to conserve wildlife and habitat. SWG provides funding, and the Action Plan provides strategic guidance. SWG is now the nation's core program for preventing endangered species listings. Each Wildlife Action Plan is required to be updated every 10 years. The next update for Vermont will be in 2025. Wildlife Action Plans are centered on the identification and conservation of Species of Greatest Conservation Need (SGCN). In Vermont, six taxonomic teams with expertise in amphibians and reptiles, birds, fish, invertebrates, mammals, and plants assessed the status of native species using criteria such as rarity, population trends, threats by invasive species, disease, and habitat loss, fragmentation, or change. Additionally, a regional group assessed and assigned some species as Regional Species of Greatest Conservation Need in the Northeast. Learn more about the Vermont Wildlife Action Plan.

State and federal Threatened and Endangered species

The federal Endangered Species Act of 1973 provides for the identification, listing, and protection of both threatened and endangered species and their habitats. According to the U.S. Fish and Wildlife Service, the law was designed to prevent the extinction of vulnerable plant and animal species through the development of recovery plans and the protection of critical habitats. Vermont's Endangered Species Law was established in 1981. The statutes cover the process of listing a species as Threatened or Endangered and designating its critical habitat within the state. It establishes the Vermont Endangered Species Committee (ESC) as well as its members' advisory roles. The ESC also created state advisory groups of regional experts (Plants, Invertebrates, Reptiles and Amphibians, Mammals, Birds, Fungi, and Bryophytes). All federally listed species occurring in Vermont are also automatically listed by state law.

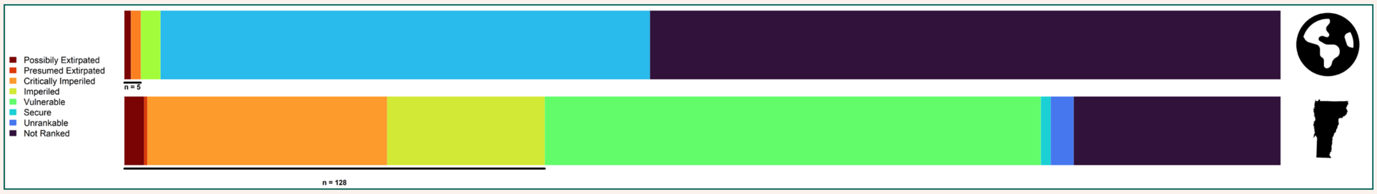
Case Study: Vermont Wild Bees

From 2012-2014 scientists at the Vermont Center for Ecostudies surveyed the bumble bee community across Vermont. Trained community scientists joined us to search thousands of locations across the state, and together we recorded more than 10,000 individual bumble bee encounters. We compared the survey data to historic specimens that we had identified to species and digitized from public and private collections. The results provided sobering news about the status of Vermont's 17 bumble bee species and led to the listing of four species as Threatened or Endangered in Vermont and one as federally Endangered. Nine species were added to the 2015 Wildlife Action Plan as Species of Greatest Conservation Need.

Bumble bees represent just a small fraction of the Vermont bee fauna. In a recent multi-year effort, VCE, the Vermont Fish and Wildlife Department, and hundreds of community scientists surveyed the entire wild bee fauna across the state. This resulted in the discovery of nearly 70 new bee species in Vermont and more than 65,000 primary biodiversity occurrence records. These efforts allowed us to assign an S-rank to 335 of the 352 native bee species in Vermont. Ten species that had no records after the year 2000 were considered to be historical or extirpated. Over 30% of Vermont's extant native bee species were ranked as critically imperiled or imperiled. Many critically imperiled species are known from just a few records, often from a single location, and with no direct information about population trends. Many of these species may be naturally rare in Vermont, making their populations susceptible to environmental perturbations. On the other end of the spectrum, nearly 23% of native bee species are apparently secure or secure. More occurrence records and threat assessments are needed to improve and clarify some of these ranks.

Armed with a robust assessment of the status of most wild bee species in Vermont, we are now able to suggest locations, habitats, and individual species that should be the highest priority for bee conservation efforts. We have developed a conservation watch list that includes 55 native bee species. Many of these species are regional specialties found nowhere else in the region, and Vermont plays an outsized role in ensuring their global survival. We modeled the distribution of most bee species in Vermont, allowing us to identify important habitats and areas with unique and diverse bee communities. Some of these areas we have proposed as Important Bee Areas, priority locations for protection, and bee-focused land management.

Learn more about our findings and see interactive maps in the State of Vermont's Wild Bees report.[9]



Predicting and mapping species of conservation concern

Species distribution maps can help determine locations that need conservation action to provide protection for species of conservation concern. We've identified areas that harbor the species most at risk, including species deemed Critically Imperiled (S1), Imperiled (S2), and Vulnerable (S3; Fig. 20).

We summarized the area of each species distribution that occurs within currently conserved lands. We found that combined, public and private conservation lands protect just over 12% of the predicted distribution for species ranked Critically Imperiled by the state. Imperiled species have a slightly larger portion of their distributions overlapping with conservation lands (17%), while Vulnerable species protection is approximately 13% (Fig. 21). The areal coverage for species of conservation concern was similar to those ranked either Secure (12%) or Apparently Secure (14%). This suggests that our conservation lands, as currently configured, may not be adequately protecting species of greatest conservation need.

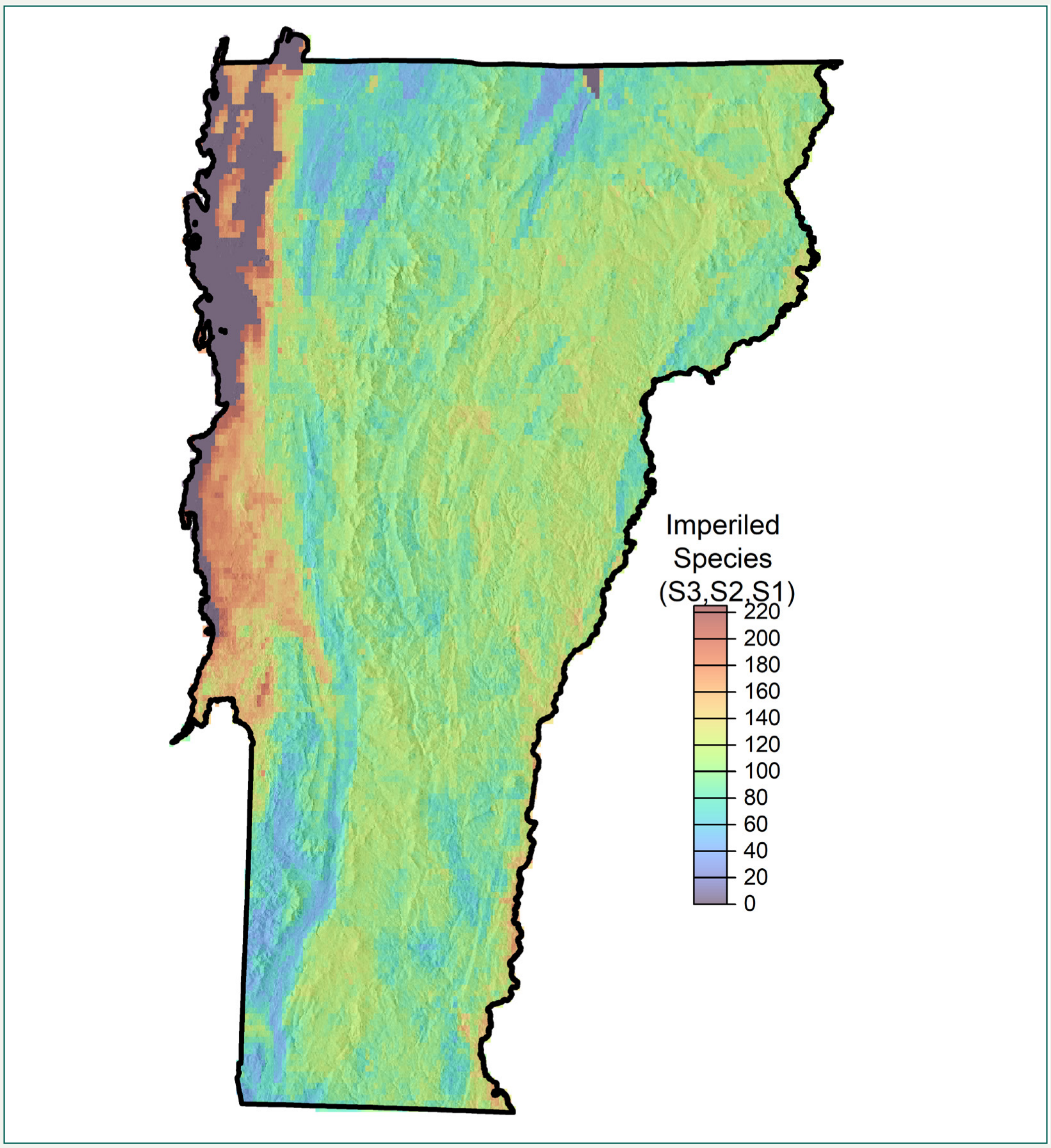


Figure 20. Map of species richness for those ranked as Critically Imperiled (S1), Imperiled (S2), and Vulnerable (S3) in Vermont.

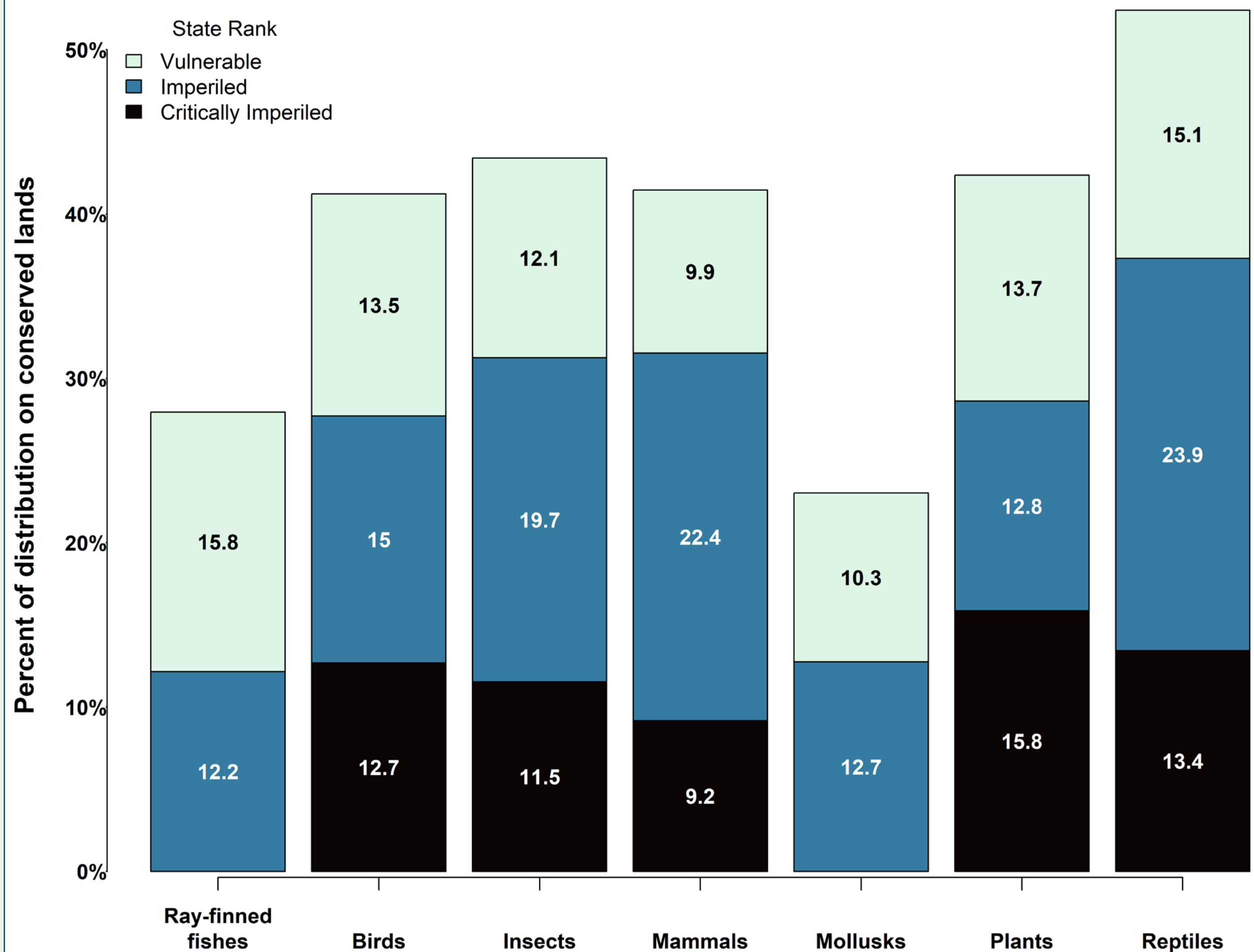


Figure 21. *A summary of the area of each species distribution that occurs within currently conserved lands that ranked as Critically Imperiled (S1), Imperiled (S2), and Vulnerable (S3) in Vermont.*

Conservation responsibility species

Partners in Flight first introduced the concept of "area responsibility" to highlight a region's share in the long-term responsibility for the conservation of certain bird species, including those that may not be on any of the conservation concern species lists.[10] Species with high proportions of their total population in Vermont are important conservation targets because the state has a large share of the responsibility for conserving the entire species.

To determine Vermont's conservation responsibility for each species, we quantified how much of its northeastern distribution occurred within Vermont. For species with large distributions encompassing the entire Northeast (New Jersey to Maine and southern Canada), the relative conservation responsibility for Vermont would be low since the species occurs throughout the region. In contrast, Vermont's conservation responsibility would be very high for species that occur nowhere else in the region. Today, the mean conservation responsibility for Vermont across all species was low (~5%) but projected to increase in the future, given the different carbon emissions scenarios (Fig. 22).

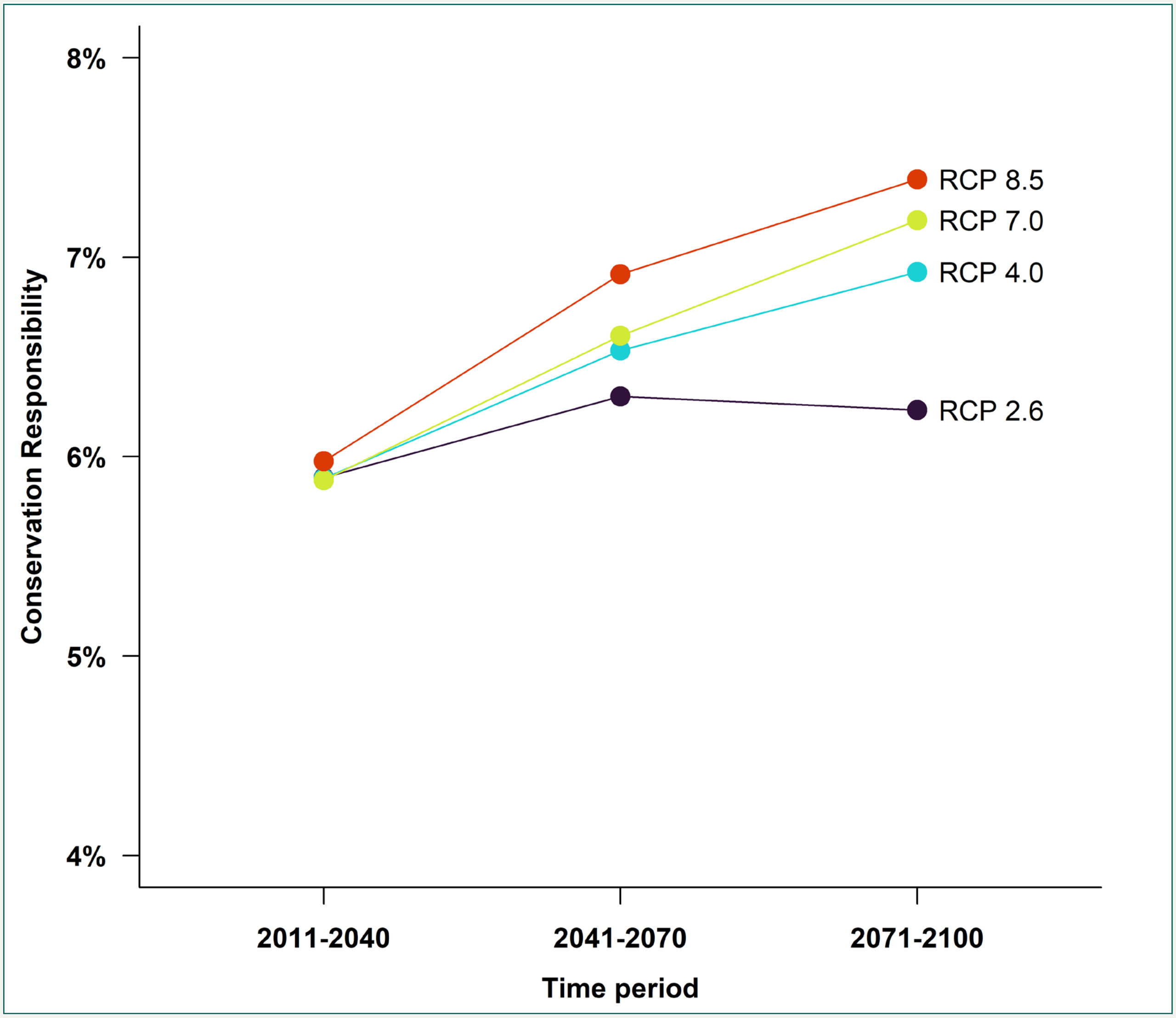


Figure 22. *We quantified percent of the northeastern distribution for each species that occurred within Vermont to determine the level of Vermont's conservation responsibility now and into the future under differing climate change scenarios. For species with large distributions encompassing the entire Northeast (New Jersey to Maine and southern Canada), the relative conservation responsibility for Vermont would be low since the species occurs throughout the region. In contrast, Vermont's conservation responsibility would be very high for species that occur nowhere else in the region.*

Vermont's conservation responsibility differs among taxonomic groups and conservation ranks. Currently, Vermont has the greatest conservation responsibility for spiders and allies (mean: 9.9%), followed by insects (6.2%), birds (5.9%), plants (5.8%), and mollusks (5.7%). Mammals and reptiles had the lowest conservation responsibility, with 3.8% and 3.3%, respectively. Species ranked as Vulnerable have a mean conservation responsibility of 6.4% and is the highest among the species of conservation concern. Critically imperiled species have a mean conservation responsibility of 6.1%, followed by imperiled species (5.5%).

While Vermont's conservation responsibility aggregated across all species was low, the persistence of some species within the region depends on actions that occur in the state. Today, the conservation responsibility for individual species is largest for a species of bee, as 95% of its Northeast distribution occurs in Vermont. Most species (85%) with a conservation responsibility greater than 50% are insects, but several plants and two mollusks have a conservation responsibility that exceeds 40%. Land-use change and policy decisions made in Vermont will play an important role in the continued occurrence of these species in the Northeast.

Vermont's Changing Climate

There is a strong link between climate and biodiversity change; each can affect the other. For example, anthropogenic changes to ecosystems can alter carbon cycles, water exchange, and nitrogen circulation, while rising temperatures and other climate impacts alter the composition, function, and structure of many ecosystems and species (McElwee, 2021).

Vermont's climate has changed over the past century, and it will continue to do so, perhaps dramatically. The 2021 Vermont Climate Assessment (VCA; Galford et al., 2021) examined the science of climate change and its impacts in the state.

Key VCA Climate Change Findings

- Vermont's annual average temperature has increased by almost 2°F (1.11°C) since 1900, with winter temperatures increasing 2.5 times faster than annual temperatures over the past 60 years and the number of very cold nights decreasing by over 7 days.
- Average annual precipitation has increased by 21% since 1900 and has become more variable in the last decade. Despite an increase in winter precipitation, annual snowfall decreased in the last ~50 years.
- Since 1960, the freeze-free period lengthened by three weeks, and the trend has accelerated to 9 days per decade since 1991.
- Lake Ice-out is 1-3 days earlier per decade on average since the 1970s and 1980s.
- Vermont experiences 2.4 more days of heavy precipitation than in the 1960s, most often in summer.
- A 2018 special report by the Intergovernmental Panel on Climate Change examined the risk of worldwide species loss for 1.5° and 2° C above pre-industrial levels. With 2°C global warming, 18% of insects, 16% of plants, and 8% of vertebrates are projected to lose over half of their climatically determined ranges. If warming is contained to 1.5°C the loss is greatly reduced to 6% of insects, 8% of plants, and 4% of vertebrates. Risks associated with other biodiversity-related factors (i.e., forest fires, extreme weather events, spread of invasive species, pests, and diseases) would also be lower at 1.5°C versus 2°C of warming, supporting a greater persistence of ecosystem services.
- The Paris Agreement is a landmark international accord that was adopted by nearly every nation to address climate change. The agreement aims to substantially reduce global greenhouse gas emissions in an effort to limit the global temperature increase in this century to 2° C above pre-industrial levels while at the same time pursuing the means to attempt to limit the increase to 1.5 degrees. We must make rapid reductions in emissions to meet this goal.

Predicting the Future

We used relationships between bioclimatic variables identified within the species distribution models to project how climate change might affect Vermont's biodiversity in the future. For this analysis, we assessed the impact of four representative concentration pathways (RCP) that represent a variety of climate scenarios, from drastically reduced carbon emissions (RCP 2.6) to continuation of business as usual without any reductions (RCP 8.5). For example, RCP 8.5 is associated with rising carbon emissions resulting in an average global rise in temperature of 4.3° C by the year 2100, while RCP 4.5 is characterized by slowly declining carbon emissions with an average global temperature rise of 2.4°C.[11] These predictions can help decision-makers make informed policy decisions and prioritize conservation efforts today that will benefit wildlife populations in the future.

Species respond to climate change by either expanding or shifting their distributions higher in elevation, poleward, or both.[12] This phenomenon is ongoing and will likely increase in the future as climate change continues. Species with distributions currently found south of Vermont will likely expand or shift northward and occur within the state by the end of the century. Inevitably, the distributions of species that currently occur in Vermont may shift as well, resulting in the loss of some species. It's impossible to know how individual species will respond to climate change. Nonetheless, predictive models built from the best available information can help focus and align conservation efforts across sectors and jurisdictions. As knowledge increases, predictions improve and become increasingly useful for managing biodiversity in an adaptive way.

We limited the species in our analysis to those that (1) currently occur elsewhere in New England and (2) were represented by five or more independent occurrence records with location uncertainty less than 0.25 miles (400 meters). We used the predictions to identify species that may occur in Vermont in the future and assess how the state's biodiversity may change over time.

Of the 7,211 species with available distributions, 6,372 are currently present in Vermont. However, the number of those species predicted to be in Vermont by 2100 falls 6% to 5,986 species under the business-as-usual carbon emission scenario (RCP 8.5), suggesting a possible net loss of about 386 species.

Insects are expected to undergo the greatest change in the future. Over 600 insect species (n = 632) that currently occur within Vermont are predicted to no longer occur here by 2100, given current carbon emissions. Poleward movements could bring over 250 new species of insects (n = 272) to Vermont, resulting in an estimated net loss of 360 insect species (Fig. 23). These are conservative estimates since only 22% (n = 3,721 of 16,663 species) of insect species observed in New England met the data requirements to estimate their current and future distributions.

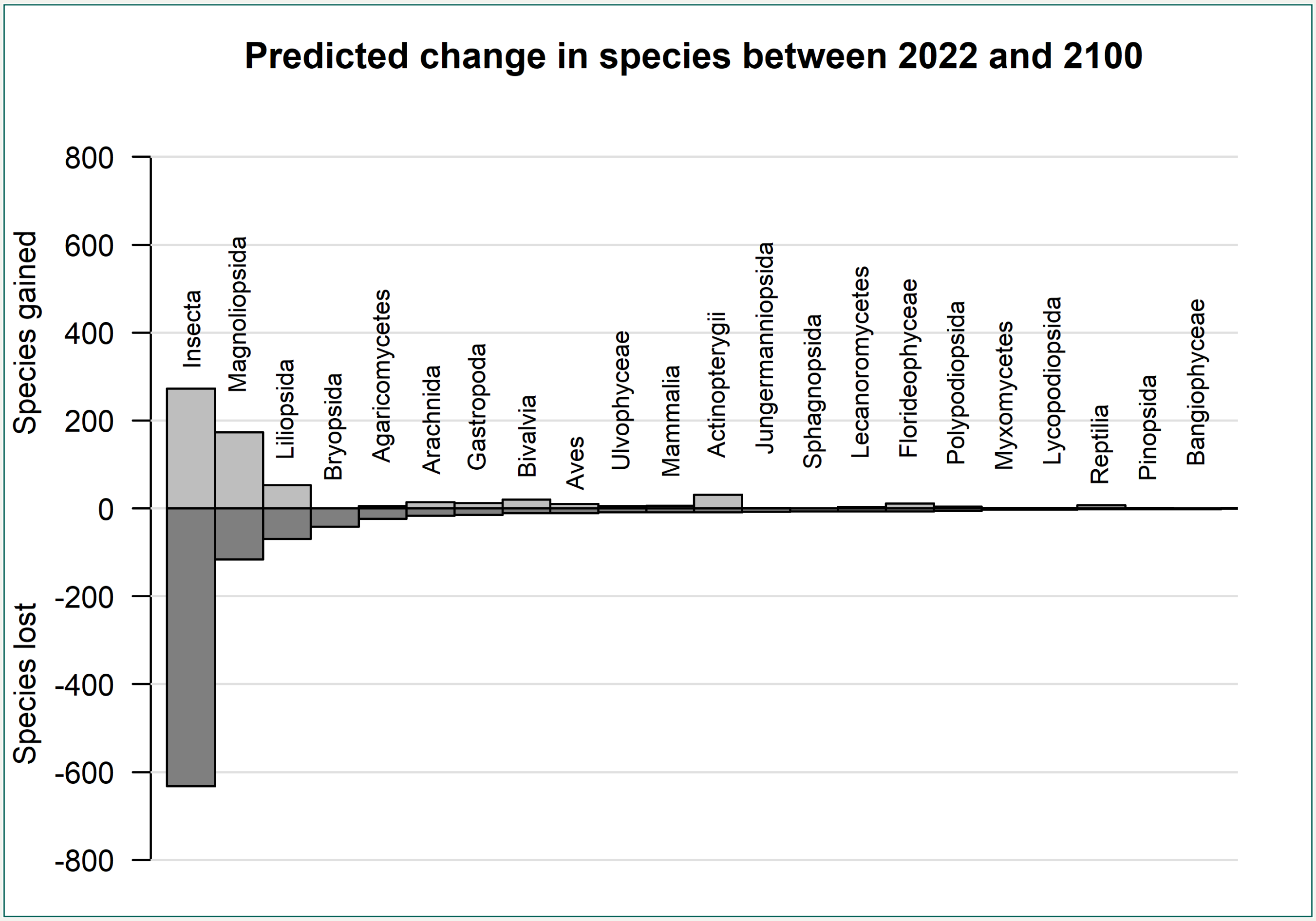
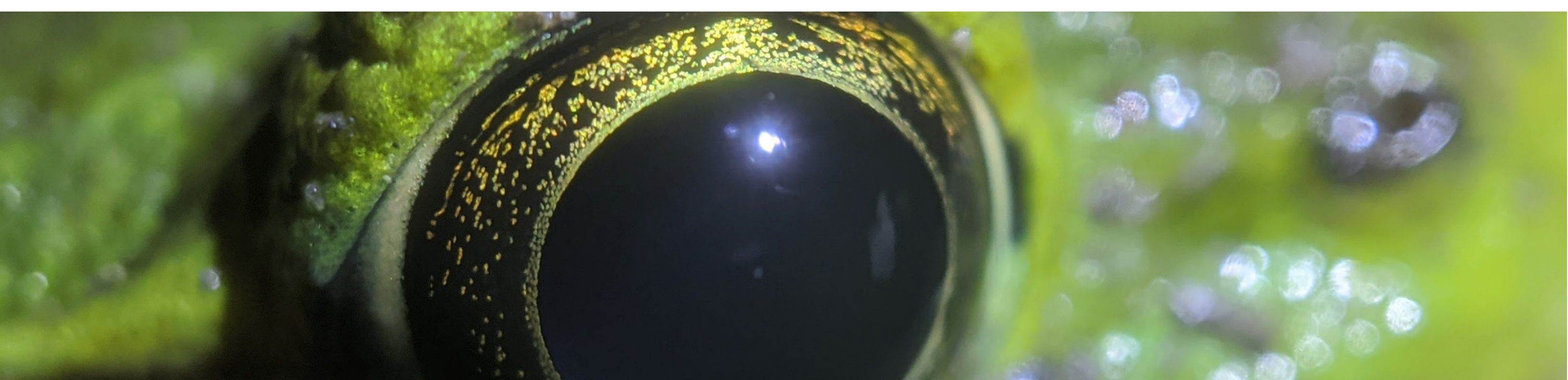


Figure 23. *We used relationships between bioclimatic variables identified within the species distribution models to project how climate change might affect Vermont's biodiversity in the future given RCP 7.0. We had enough data for 7,211 species in the northeast region. We used the predictions to identify species that may occur in Vermont in the future and assess how the state's biodiversity may change over time.*

The plant species within Magnoliopsida (a class of plants that produce two seed leaves, like oak or dandelions) and Liliopsida (a class of plants that germinate with a single seed leaf, like lilies and grasses) are also likely to change considerably. Magnoliopsida could see a net increase in the number of species within Vermont (n = 57), with 116 species anticipated to be lost and 173 gained. In contrast, Liliopsida may have a net loss of more than 15 species (n = 16) by 2100, with the potential loss of 69 species with only 53 new species possibly colonizing Vermont. These are conservative estimates since about a third, 31% (n = 1,535 of 4,857 Magnoliopsida; n = 520 of 1,747 Liliopsida) of species in these two classes met the data requirements to model their distributions.

While some species may shift their entire distributions, many are predicted to expand into areas where they do not currently occur. Mammals are the only group of organisms whose median distributions are expected to decrease (Fig. 24). In contrast, median bird and plant distributions are predicted to increase in size drastically.



The velocity of change

We measured the rate of change (km/year) between current species richness and future richness estimates. These estimates are analogous to climate velocity metrics that differ by landscape and topography. Globally, climate velocity is lower where topographic relief is high and highest where topographic relief is low.[13] Locations with a low rate of climate velocity are considered climate refugia.[12] Here, we used an analogous metric for species richness. We defined areas with a low rate of change as species richness refugia. These areas will likely continue to support species within each taxonomic class into the future if the habitat is available.

The mean velocity of species change was highest in the southwestern portion of Vermont along the western portion of the Green Mountains, followed by the northwestern region. These areas are expected to change rapidly between today and the year 2100 under RCP 8.5 climate predictions (Fig. 25). However, the northeast highlands and southern portions of the Champlain Valley, where the rate of change is lowest, may provide refugia for climate-sensitive species. The species richness in these areas is expected to remain similar to what is observed today, even if species composition changes over time.

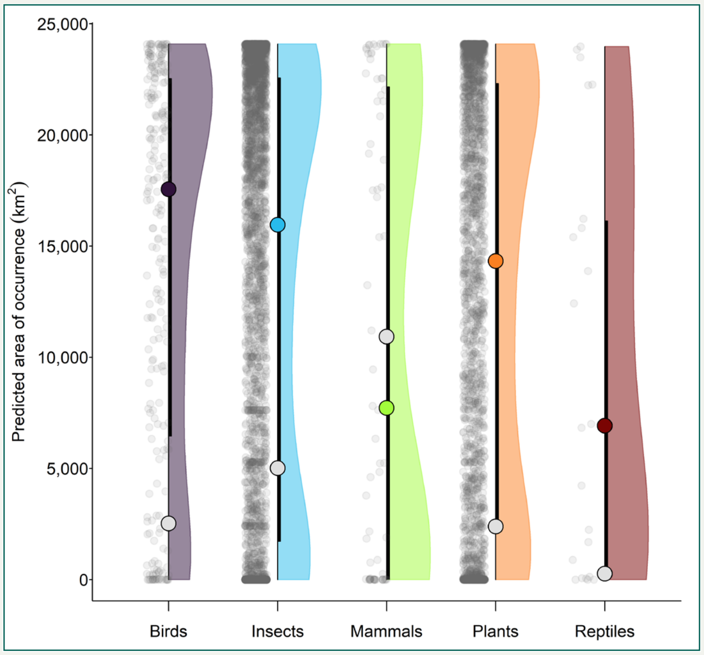


Figure 24. *We summarized the area of predicted occurrence in 2100 using Species Distribution Models. The gray dots to the left of the distribution show individual species. The large points represent the median value and the thin solid black lines represent the interquartile range while the larger black lines represent the 95% confidence interval.*

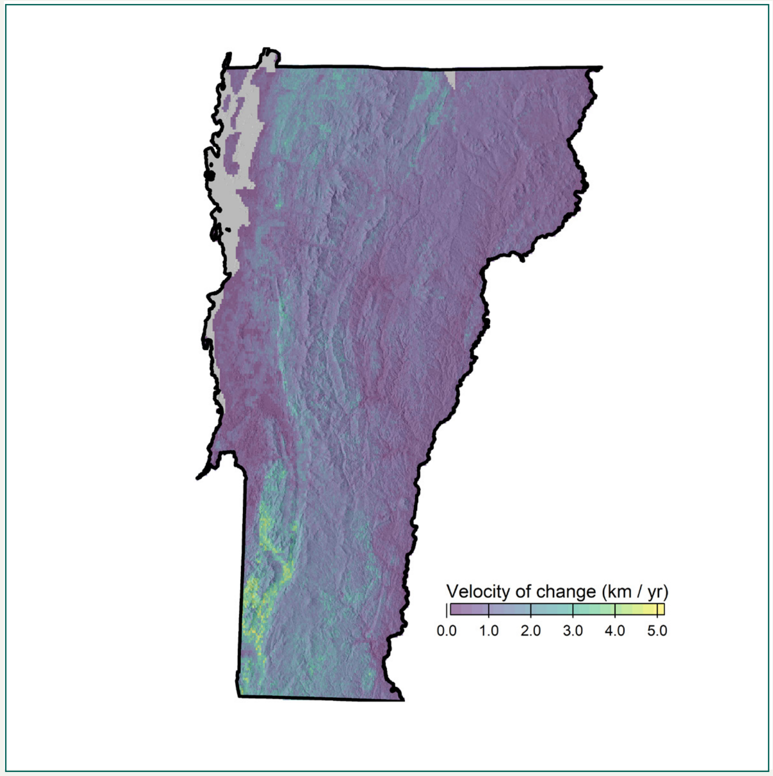


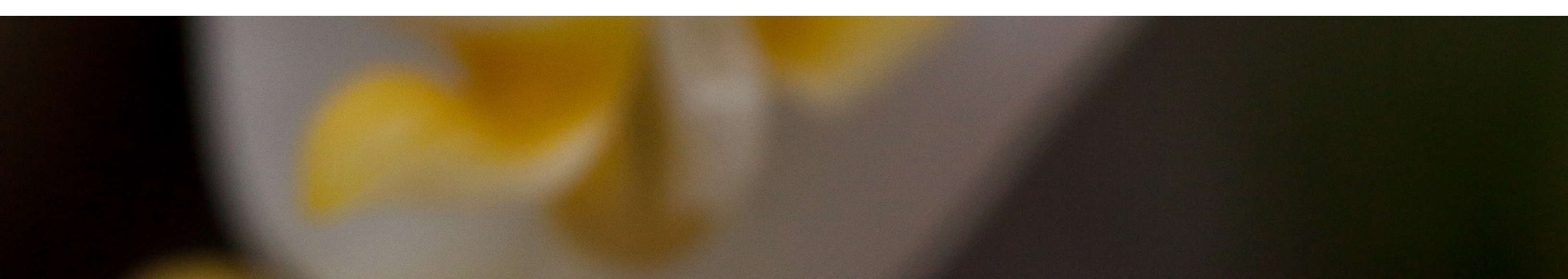
***Figure 25**. We measured the rate of change (km/year) between current species richness and future richness estimates. Locations with a low rate of change are considered climate refugia.*

Predicted change in unique communities

Climate change will likely generate novel communities composed of new combinations of species.[14] These result from varying abilities of species to adapt to changing biotic and abiotic conditions and from differential range shifts of species over time. Differential responses will change established species interactions and create new ones. Those species with specialized niches or co-evolved interactions may not be able to establish populations as readily as habitat generalists. However, there is considerable uncertainty in how and where new communities with new combinations of species and interactions will occur.

As a starting point, we used future range projections for species to identify where unique communities may occur under different climate change scenarios. We assumed conserved land parcels will remain unchanged for the next 80 years to quantify how well unique communities will be conserved in the future without additional land acquisition.

As species distributions change in response to climate change, the area and locations of unique communities will likely also change (Fig. 26). Interestingly, the median unique community area given RCP 8.5 is only slightly larger than the area currently harboring unique communities (median: 1,360.81 ± 181.75 km^2 standard error). Unique mammal communities had the lowest percentage of protection (39.8%), while unique spider and allies communities are well protected, with over 90% (94.9%) of the area falling within protected lands.



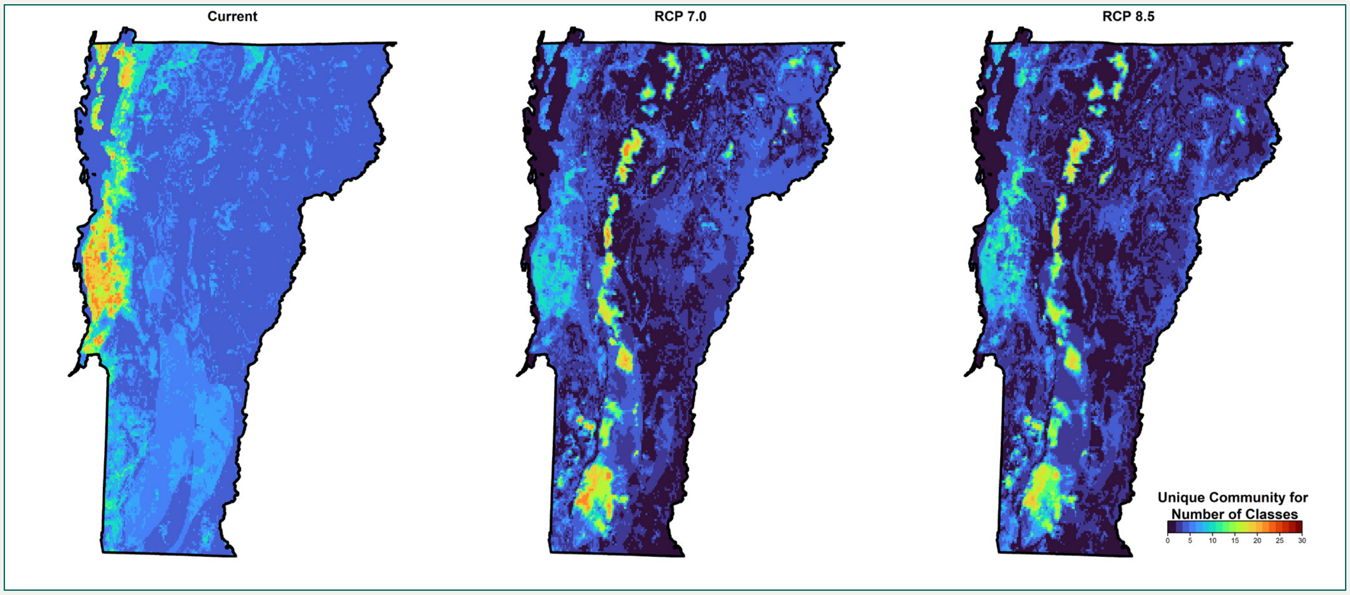


Figure 26. *As species respond to a changing climate, the areas that harbor unique communities are projected to change. Today, the southern portion of the Champlain Valley harbors unique communities for many Classes of organisms. In 2100, climate projections given moderate emissions abatement (RCP 7.0) or the business as usual scenario (RCP 8.5) suggest that areas that will have the most unique communities across taxonomic Classes shift from the Champlain Valley into the main stem of the Green Mountains and higher elevations.*

Conservation lands and future protection for species

Understanding where species may occur in the future and whether current conservation areas will protect species can help identify and prioritize areas for future conservation efforts. We used SDMs to estimate the coverage offered by current conservation lands given different climate change scenarios. Today's conservation lands will provide less protection for species, on average, in the future. By 2100, our current conservation lands are predicted to conserve approximately 11% of species distributions, down from 13% today. However, since many species distributions are predicted to increase in area, the mean area of protection increases from nearly 197,685 acres (80,000 hectares) today to as much as 345,947 acres (140,000 hectares) in 2071, given RCP 8.5.

With the planet now entering the Anthropocene, a new era characterized by rapid human-induced global change and uncertainty, conservation biologists have begun to use an important process called *landscape conservation design* to prioritize areas for conservation. These combine geospatial data, ecological information, and other information to identify areas to protect species, habitats, and environmental processes using science grounded in landscape ecology to determine where specific land conservation should be achieved. It identifies where on the landscape desired functions and opportunities exist or could exist given change and uncertainty.[15]

The Nature Conservancy's Center for Resilient Conservation Science has a landscape conservation design they call the "Resilient and Connected Network." This is a proposed conservation network across the continental United States composed of representative climate-resilient sites designed to sustain biodiversity and ecological functions into the future under a changing climate.[16] Similarly, a Vermont-based effort called the Vermont Conservation Design was first released in 2016 by state agencies and the Vermont Land Trust, which identified areas of highest priority for maintaining ecological integrity.[17] It would create a connected landscape of large and intact forests, riparian areas, and a full range of physical features for plants and animals. Both of these plans are being used to inform land acquisition and management decisions by government agencies and land trusts.

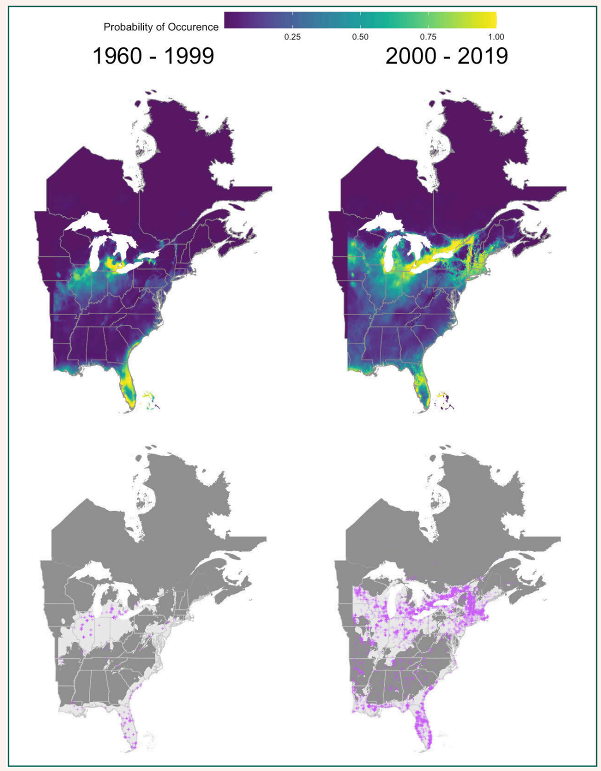
Despite the benefits of incorporating probabilistic data to explicitly account for species distribution and uncertainty in conservation prioritizations, many conservation planners have yet to employ them.[18] Incorporating probabilistic outputs of SDMs directly into prioritizations ensures that planners do not miss valuable conservation opportunities. Predictor variables from the SDMs can help uncover factors that determine their distributions and can be useful for understanding alternative actions or how robust selected prioritized areas are to potential environmental change in the future.

The conservation design paradigm has coalesced around two different approaches to conservation planning. One approach, generally referred to as a coarse-filter approach, aims to conserve landscape-scale ecological processes and heterogeneity. The other approach, often referred to as a fine-filter approach, is focused on specific species of conservation need.[19] Most landscape conservation designs for Vermont have relied on coarse- versus fine-filter conservation objectives. However, a combination of approaches will likely be needed to conserve Vermont's biodiversity into the future. In order to use a fine-filtered approach, knowledge of species distributions and habitat needs will be necessary. In the future, we will use the primary biodiversity data collected at VAL combined with species distribution models for current and predicted future environmental change for thousands of species to help assess and perhaps improve coarse-filter landscape conservation designs for Vermont.

Case Study: Expansion of the Eastern Giant Swallowtail

It's hard to miss a giant. In 2010 when the largest butterfly in North America fluttered among Vermonter's flowers at the end of July, they knew it was something neat. Photos were shared online, which later became the first record of an Eastern Giant Swallowtail (*Heraclides cresphontes*) for the state.

That first sighting was a bellwether for things to come. Now, over a decade later, the Eastern Giant Swallowtail is a regular resident butterfly in parts of Vermont and beyond—successfully breeding as far north as Montreal.



Thanks to the efforts of thousands of butterfly watchers reporting their sightings to projects such as iNaturalist.org and e-Butterfly.org, coupled with thve massive biodiversity data being shared at GBIF, we were able to study in detail the rapid flight northward by Eastern Giant Swallowtails.

Our study published in Frontiers in Ecology and Evolution showed an unusually rapid northward range shift by the butterfly. Over the course of 18 years, the range of the Eastern Giant Swallowtail moved just over 200 miles (322 km) north—a rate of expansion more than 27 times faster than an average organism.[20] The tricky thing is that while climatic conditions may allow them to continue their northward expansion, they're really restricted by their host plants.

Though sightings of adult Eastern Giant Swallowtails will likely continue to be seen further north than the naturally occurring host plant range, without a suitable host plant, further northward expansion is unlikely outside of horticultural settings. Eastern Giant Swallowtail adults lay eggs, and caterpillars feed on non-native plantings of Garden Rue (*Ruta graveolens*) and Gas Plant (*Dictamnus albus*). Common Hoptree (*Ptelea trifoliata*) is increasingly planted as an ornamental in the Northeast, yet is a native of central and southeastern North America. Although these exotic plants are not distributed uniformly across the region, dispersing giant swallowtails have an uncanny ability to find even the smallest plantings, perhaps further enabling them to expand their range in urban and suburban areas as climatic conditions allow.

Monitoring Populations

Tracking the population status and trends of biodiversity is critical both for understanding the health of the ecosystems on which we rely and identifying species and places that are most in need of conservation action. One challenge is to make sure we have robust data for as many taxonomic groups and regions as possible to monitor population trends.

While there are comprehensive monitoring projects for some species in Vermont, records of population trends for many groups are sparse or nonexistent. Additionally, for many projects, the data are not shared or fully documented and are at risk of degrading or being lost over time.

Birds are the most comprehensively monitored group across Vermont and are generally considered good indicators of the state of the environment. VAL has documented over 20 bird population monitoring projects so far. They range from thousands of semi-structured checklist surveys by bird watchers collected by Vermont eBird since 2003 to structured projects like the roadside Breeding Bird Survey, trailside high-elevation monitoring by Mountain Birdwatch, or comprehensive Breeding Bird Atlas surveys (Fig. 27).

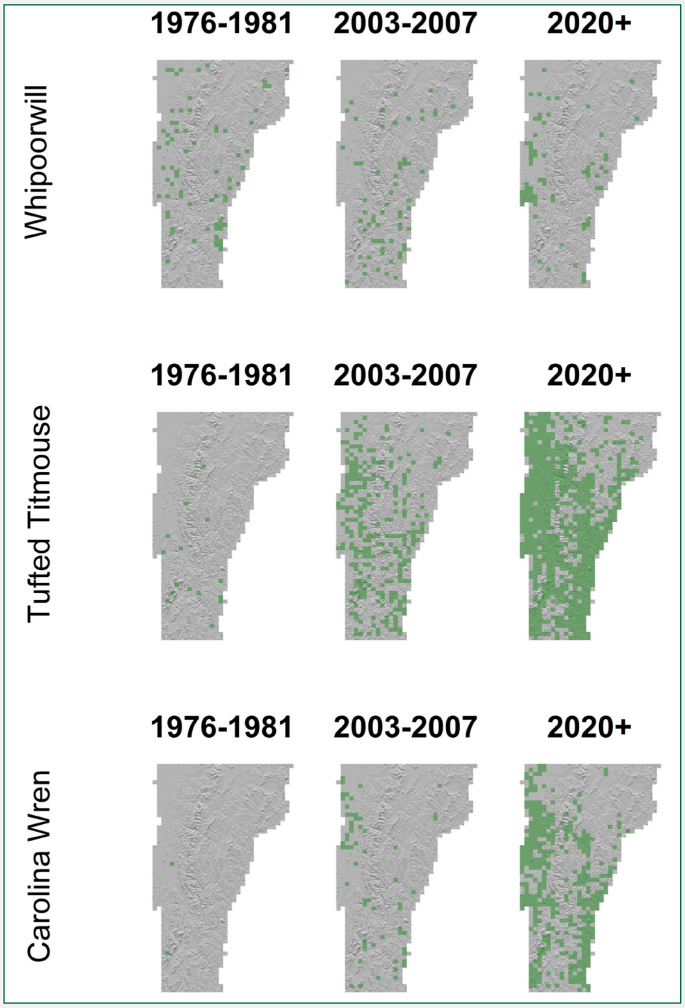


Figure 27. Examples of changes in range for three species of breeding birds from the first (1976-1981) and second (2003-2007) Vermont Breeding Bird Atlases and the latest observations in VAL (2020-2023). Changes likely have occurred from both land cover and land use (Eastern Whip-poor-will) and climate change (Tufted Titmouse and Carolina Wren).

Introducing the Living Vermont Index and Database

The Living Vermont Index will be a multi-species indicator based on average trends in population abundance of plant and animal species from

Vermont. The Living Vermont Index (LVI) is modeled after the Living Planet Index. Together, the trends that emerge will be used as a measure for change in Vermont's biodiversity. It does this in much the same way that a stock market index tracks the value of a set of shares.

To be included, the data must be from a time-series of two or more years of either population size, density (population size per unit area), abundance (number of individuals per sample) or a reliable proxy (*e.g.*, nests, tracks, capture per unit effort, measures of biomass for a single species), or occupancy data and associated models.

The building blocks for this index are stored in the Living Vermont Database, an ever-growing catalog of species population monitoring schemes and primary data gathered from a range of sources, including published scientific literature, online databases, government reports, directly from researchers and institutions, and gray literature.

We are seeking to unite as many monitoring projects as possible to build the Living Vermont Index and make available any unrestricted information in the Living Vermont Database for anyone to use for decision-making, monitoring, and conservation research.

Conclusion

The Vermont Atlas of Life began a decade ago as an ambitious and far-reaching effort to discover and map the state's biodiversity. Our goal was to bring together the loose network of community scientists, naturalists, biologists, private organizations, and public agencies collecting biodiversity data in Vermont to create the largest biodiversity database ever assembled for the state. Our hope was that we could jump-start biodiversity conservation for all species, much like the Breeding Bird Survey did for land bird conservation.

Nearly 60 years ago, Chandler Robbins at the Migratory Bird Population Station had an idea that would change bird conservation in North America. He and his colleagues developed and launched the Breeding Bird Survey (BBS), a program to monitor breeding bird populations across the continent using roadside survey routes. Today, thousands of expert bird watchers volunteer to rise before dawn one day each summer to count birds on over 3,000 routes, 23 of them in Vermont. Today, the BBS is our longest-running continental bird monitoring program, the bellwether for bird populations across Vermont and beyond (Fig. 28). Without the BBS, we wouldn't know that we've lost nearly 3 billion birds in North America since 1970, or more than 1 in 4 individuals, nor that eastern forest birds have declined by 17%.[21]

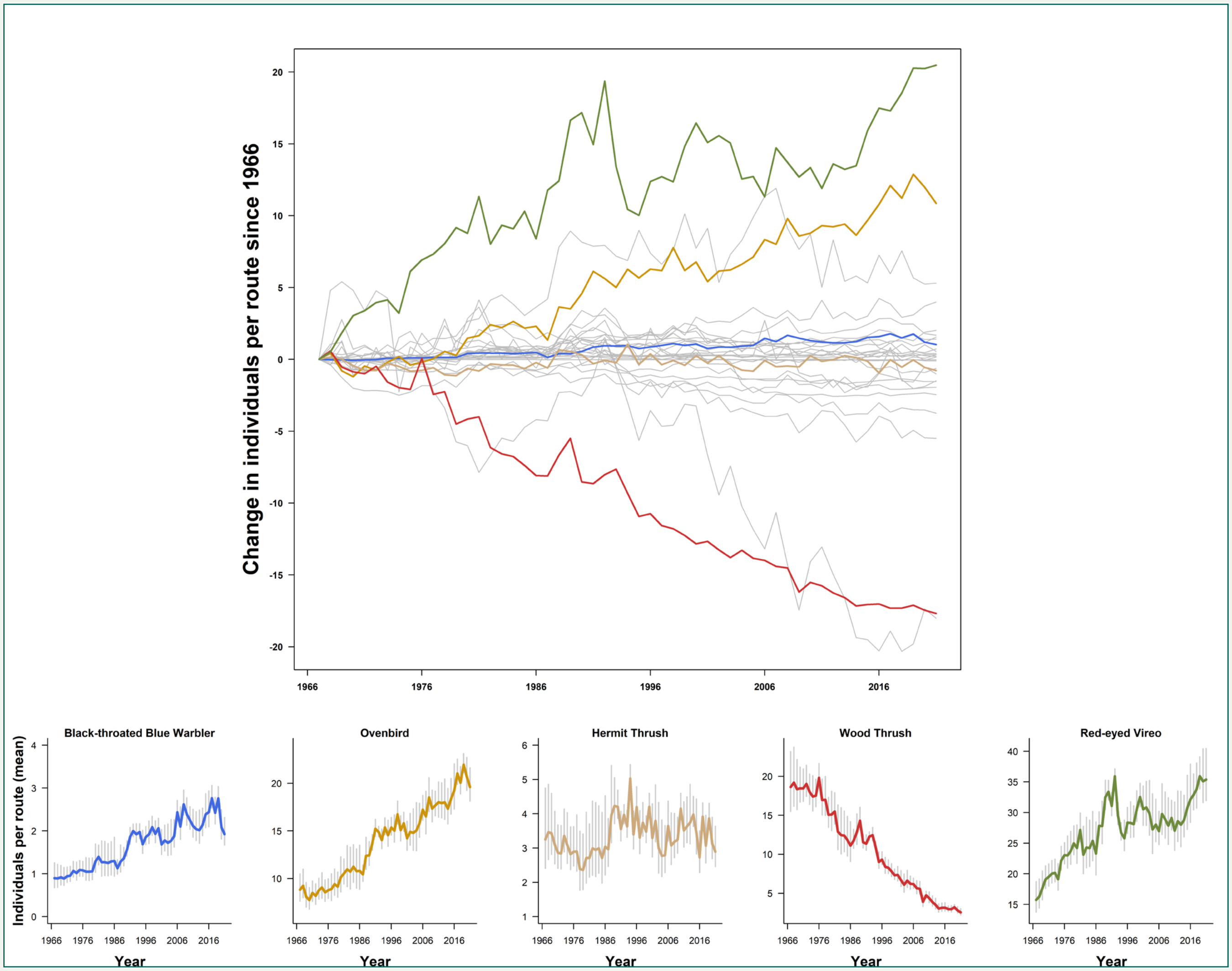


Figure 28. *Volunteers have been participating in the Breed Bird Survey in Vermont since 1966. The number of individuals for some bird species has changed considerably while others have remained similar though time (top figure). Structured data collected through time allows scientists to estimate population trends. The mean number of individuals per Vermont Breeding Bird Survey routes for a few, iconic, forest breeding species are shown in the bottom figures. A few species show alarming declines while others are increasing highlighting the importance of long-term monitoring programs.*

Birds are one of the best-studied groups of wildlife. From the BBS to eBird, Mountain Birdwatch to the Vermont Forest Bird Monitoring Program, and from many others in between—the data we have available are remarkable, and they allow us to focus conservation efforts where they are needed most. But what about the rest of biodiversity? This question was the impetus for hatching VAL a decade ago.

VAL is gathering essential data for biodiversity conservation and has amassed almost 8 million records of nearly 12,000 species (11,993 species)—all curated at GBIF and searchable using the VAL Data Explorer. Although these records are derived from many sources, from historical museum specimens to field observations, over 95% are submitted by community scientists through VAL-supported platforms like Vermont eBird, iNaturalist, and e-Butterfly. Vermonters have risen to the conservation challenge as our community scientists lead the nation, with more field observations per capita than any other state.

An important aspect of VAL that can easily be overlooked is how it connects thousands of people to nature. There is a growing awareness of the importance of people's active engagement with nature that benefits their health and well-being. As community scientists are helping us to gather massive amounts of biodiversity data, they also are becoming more engaged and invested in conserving it.

Climate and land-use change, coupled with a myriad of other environmental issues, are presenting significant conservation challenges that require an understanding of species populations at large scales. Identifying current and impending threats and evaluating outcomes from conservation actions can only be done with massive data efforts at multiple spatial and temporal scales. The ability to manage, and manipulate vast, near real-time data resources is changing how biodiversity research and monitoring is conducted and has the potential to revolutionize conservation practices. Through partnerships between scientists and the public, the Vermont Atlas of Life is providing this information now and peering far into the future.

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Suggested citation: Hallworth, Michael T., Kent P. McFarland, Spencer Hardy, Nathaniel Sharp, Emily Anderson, Jason Loomis (2023). *Vermont Atlas of Life: 10th Anniversary Report*. Vermont Center for Ecostudies. https://doi.org/10.6084/m9.figshare.23498652.v1