An Environmental and Economic Systems Analysis of Land Use Decisions in the Massachusetts Cranberry Industry

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Submitted to the Program in Media Arts and Sciences,
School of Architecture and Planning,
in partial fulfillment of the requirements for the degree of

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Abstract

This dissertation presents an analysis of the environmental and economic impacts of land use decisions in the Massachusetts (MA) cranberry industry. Cranberry farming is culturally and economically important in Southeastern MA but faces ongoing, compounding challenges that make it increasingly difficult for farms to stay profitable: heightened competition from Midwestern farms using modern farming techniques, fluctuating cranberry prices, an aging farmer population, and climate change.

These factors have led many farmers to consider new options for their farmland including undergoing farm renovations, selling their land to developers, or partnering with conservation organizations to restore their farmland to its native wetland state. Given the scale of the cranberry industry and the amount of ecologically valuable yet vulnerable land at stake, farmers, local governments, and environmental advocacy groups alike need higher quality information and tools to inform land use decisions.

Building on the science of cranberry bog restoration and incorporating perspectives from across the cranberry industry, this thesis applies ecosystem service modeling to geospatial data to quantify environmental outcomes in this decision space and make an economic argument for restoration. In the first section of the thesis, I conduct stakeholder interviews and a literature review to identify socioeconomic contextual issues and industry stakeholder objectives. Next, guided by the Environment-Vulnerability-Decision-Technology framework, I use open-source ecosystem service models applied to public satellite imagery to model and analyze the environmental and economic impacts of different land use scenarios and identify priority restoration areas. Finally, I present and evaluate the results of this modeling work in a web-based decision-support tool that allows stakeholders to interact with and explore different land use outcomes.

Integrating tools from diverse disciplines, this research presents novel, spatially-explicit analysis on the impacts of land use decisions in the MA cranberry region and identifies areas where restoration could generate environmental and economic synergies. With this work, I aim to deliver practical data tools that will incentivize sustainable decision-making, address knowledge gaps in the MA cranberry industry, and contribute to broader discussions around natural climate solutions and agricultural land retirement, two topics of urgent and relevant interest in the fight against climate change.

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The kindest, bravest, most patient woman I know.

I love you more than all the leaves on all the trees.

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Chapter 1

Introduction

1.1 Motivation

This dissertation is motivated by a desire to address the complex, interconnected challenges of climate change and agriculture by exploring the environmental, economic, and social tradeoffs and synergies that arise from different uses of land. These issues are tackled in the context of the Massachusetts (MA) cranberry industry, which occupies a position of economic, cultural, and historical importance in Southeastern MA, but today faces challenges that are changing the dynamics of production and the calculus of agricultural land use for growers. Blending methods from systems engineering, environmental economics, and data science, this dissertation explores the environmental impacts of land use decisions in the MA cranberry industry, develops tools to support climate-friendly decision-making, and contributes academic and practical knowledge to ongoing conversations around the future of the MA cranberry industry, natural climate solutions, and sustainable land use.

The world is now well-aware of the devastating threats of anthropogenic climate change, which are already presenting themselves in non-linear and regressive ways. Rising sea levels, fire, drought, and more frequent extreme weather events are disrupting our economic, agricultural, and industrial systems, spurring immigration and upheaval, and threatening our most vulnerable ecosystems and communities (IPCC, 2022). While our way of life and systems of production face serious risks, it is also these systems that generate the emissions contributing to climate change; to avert the worst impacts of climate change, we must break the vicious cycle of consumption and penalty-free destruction that have fueled industrial and post-industrial capitalism, and start accounting for and protecting the natural world.

This dissertation focuses in particular on the agriculture, forestry, and land use space. Activities in this area are responsible for about a quarter of annual greenhouse gas emissions, as well as large historical emissions (IPCC, 2022; Houghton & Nassikas, 2017). A large portion of agriculture-related emissions are due to deforestation in the service of agricultural expansion; when forests are cleared or burnt, the carbon stored in trees is released into the atmosphere. Emissions can also be ascribed to agricultural activities and processes themselves, including chemical fertilizer production, methane release from ruminant animals and manure, and other processes and activities deeply embedded in our current production systems. In addition to contributing to global fossil fuel emissions, activities related to agriculture and land use often have destructive local environmental impacts, causing soil erosion, leading to nutrient pollution, and putting strain on fragile local and regional water supplies (Pimentel & Pimentel, 1990; Cordell, Drangert, & White, 2009; Rosa, Chiarelli, Rulli, Dell'Angelo, & D'Odorico, 2020).

Despite the destructive and polluting nature of our agricultural systems, food production cannot simply be paused or scaled back. Indeed, models of global population growth and changing dietary preferences suggest that food systems will actually need to produce around 50% more food by mid-century, relative to 2010 (Cleland, 2013). In the past century, increased agricultural production has been made possible through the expansion of agricultural areas, or increased application of chemical fertilizers and pesticides, both of which contribute to environmental damage and greenhouse gas emissions (Pimentel & Pimentel, 1990). Thus, a major challenge of the food world is ensuring food security without exacerbating pressure on scarce water and land resources (Ringler, Bhaduri, & Lawford, 2013). Reconciling these competing pressures will require thoughtful trade-offs, novel technologies, and targeted, regional approaches (Seufert & Ramankutty, 2017; Davis, Rulli, Seveso, & D'Odorico, 2017).

The idea of "land use" – simply, how any given area of land is used, whether for agriculture, forest, housing, or more – is central to many of the challenges and conversations around climate and agriculture. Agricultural production is intimately tied to the land, and represents a major global land use: 40% of the global land surface is used for agriculture (Food and Agriculture

Organization of the United Nations, 2022). Land use is also closely tied to GHG fluxes; some uses of land, such as forest or wetlands, are major sinks and stores of carbon, while other uses of land, such as industrial uses, tend to contribute to GHG emissions. Thus, the way that land is used can have a major impact on climate change and the health of natural environments.

The decisions that lead to different land use lie at the nexus of economic pressures, government policy, urbanization, and more. Deciphering land use decision-making, and guiding these processes towards more sustainable outcomes, are important levers for mitigating GHG emissions, and are central to many discussions of climate change and agriculture. Malek et al. (2019) describe how land use decision-makers, often individual land owners, are "influenced by a variety of context-specific socioeconomic" factors, but most frequently driven by the need to survive and maintain their livelihood, and both internal and external economic and political factors. Decisions such as which crops to grow can be driven by economic considerations like demand or profits. Land-use changes with detrimental environmental impacts, like agricultural intensification and deforestation, are frequently driven by economic and political forces, because fewer decision-makers are able to prioritize environmental concerns. As a result, changes in land-use frequently involve environmental sacrifices in pursuit of economic objectives. For example, skyrocketing global demand for soybeans and palm oil has led to widespread deforestation in Brazil and Indonesia to create more space to produce these commodities (Barona, Ramankutty, Hyman, & Coomes, 2010; Vijay, Pimm, Jenkins, & Smith, 2016).

At the same time, changes in the climate are altering the global calculus around optimal agricultural areas, with climbing temperatures opening up new regions for growing that had previously been too cold for agriculture, while making other areas increasingly inhospitable to agriculture (Ruane & Rosenzweig, 2018). Under a changing climate and more extreme drought conditions, sometimes the question for growers is whether to produce crops at all. For example, due to extreme drought in the Western United States, some rice and almond farmers in California are confronting the question of whether to grow crops, or simply sell their lucrative water rights for the season (Sengupta, 2021). Due to the changing climate and land degradation, there is predicted to be widespread abandonment of agricultural land in the coming decades. With so much acreage predicted to pass out of agricultural use, there is broad interest in using *ecological restoration* in these post-agricultural areas to mitigate climate change and protect biodiversity (Yang et al., 2020; Strassburg et al., 2020; Beyer, Hua, Martin, Manica, & Rademacher, 2022). Ecological restoration involves targeted human interventions to repair degraded environments, rehabilitate native ecosystem function, and support biodiversity (SER, 2002). In the context of agricultural land use decisions, however, one of the key challenges for ecological restoration projects is developing the financial incentives to make these projects attractive to individual land owners.

This dissertation explores approaches that align environmental objectives with the economic needs of land use decision-makers. One way of doing this is to recognize and internalize the value of *ecosystem services*, which are the services and goods that humans receive from natural ecosystems. While many believe natural ecosystems have intrinsic value, the idea of ecosystem services explicitly (but not exclusively) ties the value of ecosystems to the services they can provide to humans. For example, some of the ecosystem services provided by wetlands include water purification, soil carbon storage, and flood mitigation (Russi D. ten Brink P. & N., 2013). Though some critics decry this "commodification of nature", the quantification of ecosystem services has become a widely used tool in analyzing trade-offs and performing cost-benefit analyses in environmental policy-making in recent decades (McCauley, 2006; Swiss Re Institute, 2021).

In addition to being used in policy-making, when ecosystem services are assigned an economic value, they can be traded in a market setting. For example, starting in 1990, there have been more than forty markets that allow agricultural producers or other entities to trade water quality credits (Ribaudo, Hansen, Hellerstein, & Greene, 2008). More recently, there has been an explosion in voluntary carbon offset and credit markets, which allow companies, individuals, or other entities to trade the right to emit carbon or the ability to sequester a ton of carbon (Streck, 2021). In many of these cases, markets that sell carbon credits are tied to the ability of a specific ecosystem to sequester carbon, such as agricultural soil carbon sequestration or afforestation initiatives. There are also instances of direct payments for ecosystem services, as in the case of the Conservation Reserve Program (CRP), a United States Department of Agriculture (USDA) program that pays farmers to "remove environmentally sensitive land from agricultural production and plant species that will improve environmental health and quality" in order to “improve water quality, prevent soil erosion, and reduce loss of wildlife habitat” (USDA Farm Service Agency, 2021).

The challenges around land use trade-offs are both global in that they happen everywhere and, in the aggregate, have global implications, but also local, because decisions are strongly dependent on region-specific context and policy. Many of these threads come together in the study of wetland restoration in the context of the MA cranberry industry, where the environmental and economic stakes of land use are heightened due to the ecological history of the industry: most cranberry farms in the region were constructed on top of native freshwater wetlands over a century ago. Today, the MA cranberry industry encompasses around 13,500 acres of farmland, and occupies a position of economic and sociocultural importance in the region, with a total economic impact of around $1.4 billion (Massachusetts Department of Agricultural Resources, 2016). However, the industry faces compounding challenges that have made it increasingly difficult for farms to stay profitable: heightened competition from Midwestern farms using modern farming techniques and hybrid cranberry cultivars, fluctuating cranberry prices, an aging farmer population, and uncertain growing conditions due to a changing climate (Massachusetts Department of Agricultural Resources, 2016).

These factors have led many farmers to experiment with new ways to improve profitability or earn income: undergoing farm renovations to improve efficiency, planting newer and more robust cranberry varietals, or diversifying their income streams with solar panel installation or alternative crops (Massachusetts Department of Agricultural Resources, 2016). Other farmers, looking to exit the farming industry entirely, have several options. One is to sell their land to residential or commercial developers. However, the financial upsides of real estate development on former cranberry bogs can be limited due to federal limitations on developing wetlands; thus the development potential of any given parcel is tied to the upland (i.e. non-wetland) areas adjacent to wetland farms. Another option for farmers is to partner with local municipalities, conservation NGOs, and the MA Department of Ecological Restoration (MA DER) to restore their farmland to its native wetland state. If and when farms are retired from production, there is an opportunity to remove the anthropogenic artifacts of farming, and restore the beneficial ecosystem services of a functioning wetland environment, which could include water purification, biodiversity support, and carbon sequestration, among others (K. Ballantine, Deegan, Gladfelter, Hatch, & Kennedy, 2020). These ecosystem services are particularly relevant given some of the environmental challenges in this low-lying, coastal region, including significant aquatic pollution. While the restoration option is exciting to scientists and environmental advocates, there is a need to build the scientific, technical, institutional, and funding capacity to achieve wetland restoration at scale in MA.

My research lab, the Responsive Environments Group at the Media Lab, has had a front row seat to the freshwater wetland restoration process through nearly a decade of work on the Tidmarsh Farms restoration project in Plymouth, MA. Tidmarsh was a century-old cranberry farm built on top of natural wetland, and as of today, is one of only four cranberry farms in the state to have undergone a restoration (K. Ballantine et al., 2020). To learn about the restoration process, and explore how people could interact with this changing ecosystem, our group instrumented the 600-acre Tidmarsh site with a custom low-power sensor network that gathered data on soil moisture, temperature, humidity, and more (B. Mayton et al., 2017). Through this work, our group has been able to join and collaborate with other researchers and stakeholders in the Living Observatory (LO) group, a collective of scientists, artists, and practitioners studying and documenting the cranberry bog restoration process. Other members of LO, which draws its diverse membership from universities, NGOs, and government agencies, have conducted wide-ranging research on the ecological impacts of cranberry farm restoration (K. Ballantine et al., 2020).

As part of my dissertation research, I conducted interviews with stakeholders in the cranberry community, including farmers, scientists, restoration practitioners, and business-people. I learned about current challenges and opportunities in the MA cranberry. Faced with the colliding trends of climate change, unstable cranberry prices, and the potential for significant agricultural land retirement, I found that many stakeholders had distinct yet overlapping objectives. Many farmers expressed the need for a financially sustainable retirement. Town leaders were motivated by improving water quality, while many NGOs sought to increase protected conservation acreage. All these stakeholders co-exist within the region, collaborating, interacting, and making decisions driven by their own objectives. I was intrigued by this challenging decision space. The cultural significance of the cranberry industry and the ecological vulnerability of wetlands heightened the stakes of farmer decisions, but also made those decisions more murky and difficult.

I observed significant interest in the wetland restoration of cranberry bogs, paired with uncertainty about how to fund and operationalize this process while respecting the needs and autonomy of cranberry farmers. While restoration would seem to satisfy the needs of many stakeholders, the question of how to fund it emerged as a key challenge. The approach put forward in this dissertation, which draws on methods from resource and environmental economics, was to quantify, in economic terms, the real value generated for the community from the ecosystem services supplied by a wetland restoration (Farber, Costanza, & Wilson, 2002). When these values are named, measured, and monitored—and conversely, when the costs of ecosystem harms are internalized through taxes or fines—we can align our economic needs as a society with the imperative to conserve and protect the natural environment. This idea is a core tenet of environmental economics; in this dissertation, I build tools and conduct analysis to ground and operationalize this concept in the context of the MA cranberry industry.

My own interest in and approach to these issues comes from studying human behavior and sustainable decision-making. Sep Kamvar, my first advisor at the Media Lab, wrote about creating metrics that embody the values of your system, because metrics that are measured are the ones the system is designed to optimize (Kamvar, 2021). Early in graduate school, I was also exposed to Charles Eisenstein's writing on commons-backed currency, where he postulates an economic store of value backed by natural capital, such as the right to emit GHGs or the right to harvest a certain amount of fish or the right to withdraw water from an aquifer (Eisenstein, 2021). I appreciated the elegance of the idea that assigning economic value to an environmental asset would nudge our market-driven society to optimize for that asset.

The idea of measuring, monitoring, and rewarding sustainable behavior and natural capital is a common thread connecting many of the diverse projects I have worked on during graduate school. Throughout this time, I have come to understand some of the challenges of implementing these ideas in a real-world setting: accurately monitoring and measuring natural assets is often a difficult technical feat; the financial structures to support ecosystem services may not exist or are underfunded; individual decision-makers are complex, habit-driven, and not perfectly rational; stakeholders may have conflicting or competing needs. I have tried to take some of these challenges into account in the design of this dissertation.

In particular, I have taken what might be called a "participatory systems engineering" approach that combines aspects of systems engineering with a focus on context awareness and stakeholder analysis. I draw on the *Systems Architecture Framework* to conduct a contextual analysis of the MA cranberry industry, identifying key stakeholders and their needs (Rechtin & Maier, 2010). Next, I use the *Environment-Vulnerability-Decision-Technology* (EVDT) framework to design my analysis of environmental and economic impacts of land use in the region. This framework, developed in the Space Enabled Group at the Media Lab, is well-suited to multi-stakeholder environments, and provides a structured approach for integrating environmental and socioeconomic data (J. B. Reid & Wood, 2020a). Finally, I draw inspiration and best practices from geospatial data visualization and usability research to design, develop, and evaluate a data tool for stakeholders (J. B. Reid & Wood, 2020a; Climate Interactive, 2022).

By using these methods to frame my study of land use in the region, I aim to conduct relevant analysis and build useful tools for the MA cranberry community, as well as develop insights to support sustainable land use in the abstract. The MA cranberry use case was selected as the focus of this dissertation partially because of my research group's involvement in ongoing restoration research in the region, but also because there are several qualities of the cranberry case study that make it more broadly relevant to other land use decision-making settings. First, as is the case in many land use decision scenarios, the MA cranberry industry involves multiple stakeholders with both competing and collaborative aims, unequal financial and political leverage, and asymmetrical information. The multi-stakeholder nature of the case speaks to the need for flexible, accessible, and data-rich tools. Second, these stakeholders often need to make decisions under uncertainty, with limited information about future conditions, which indicates a need for tools and analysis that can incorporate diverse data, and balance uncertainty with utility. Finally, I believe we are reaching an important confluence of awareness and urgency around climate change mitigation and biodiversity protection. As society increasingly invests in the technological and financial systems that recognize and reward the value of the environment, there will be a need for processes and tools to operationalize and implement these systems.

While the idea of internalizing the economic value of ecosystem services is not a silver bullet solution to the intertwined challenges of climate change, food production, and land use, it is an intriguing idea that has begun to enter the mainstream with an increasing number of restoration and conservation markets and incentive schemes (Forest Trends Association, 2022). Through stakeholder conversations, ecosystem service analysis, and the development of user-friendly tools, I lay the groundwork in this dissertation for a process that values and rewards ecosystem services in the Southeastern MA cranberry region. My work asks: *What are the ecosystem services that stakeholders need and value? What is the potential value of these services under a restoration program? How can this value most effectively be communicated to key stakeholders and decision-makers?* This dissertation is a first step towards applying the lens of ecosystem service valuation to the wetland restoration effort in MA, and giving stakeholders and decision-makers the information and tools they need to align environmental and economic objectives.

1.2 Contributions

With this thesis, I aim to conduct a holistic analysis that takes into account the objectives of cranberry industry stakeholders and advances an economic argument for the wetland restoration program. This dissertation addresses gaps in several bodies of literature, including the study of cranberry bog restoration in MA and the development and validation of the EVDT framework. I undertake three research efforts that build towards these goals. First, using methods from systems engineering and social science, I conduct a contextual analysis of the industry to identify the key objectives and needs of stakeholders in the MA cranberry industry and surrounding region. Second, I leverage the EVDT integrated modeling framework to investigate the environmental and economic impacts of different land-use scenarios. At the time of writing, this is the first published doctoral thesis to implement and demonstrate the EVDT framework. To use this framework, I employ ecosystem service models that unite socioeconomic and environmental data to understand the diverse impacts of farming and restoration. Finally, I develop and evaluate an interactive web-based tool that allows stakeholders to explore these impacts and provides geospatial insights into key land use scenarios.

The aim of this thesis is to provide region-specific analysis to help clarify the circumstances of this particular industry and scenario, in line with current calls for locally-adapted, regional scale climate solutions. At the same time, by analyzing a region and industry, that, by virtue of their historical, environmental, and agricultural qualities presents a particularly relevant and high-stakes version of land-use trade-offs, this work offers a blueprint for how to approach similar issues of agricultural land use and sustainable decision-making as they arise around the country and the world.

1.3 Dissertation Overview

This dissertation draws contextual inspiration and methodological grounds from a variety of sources. After this introduction, in Chapter 2, I discuss the contextual background of this work, including climate change, the MA cranberry industry, and wetland restoration science. In Chapter 3, I discuss the methodological framework of this research, including systems engineering, ecosystem service valuation, and geospatial data exploration tools. In the subsequent three chapters, I detail the three research efforts that make up this body of work: in Chapter 4, the *Systems Architecture Framework* analysis of the MA cranberry industry; in Chapter 5, ecosystem service estimation and valuation under different wetland restoration scenarios; and in Chapter 6, the development and evaluation of a web-based data explorer and decision-support system. This dissertation closes with Chapter 7, in which I present contributions of the work, discuss challenges, and point to a future research agenda.

Chapter 2

Context Area Background

2.1 The Intertwined Challenges of Climate Change and Agriculture

The study of climate and anthropogenic climate change is a vast, established, and sprawling field. Greenhouse gases (GHGs) – including carbon dioxide, methane, and nitrous oxide – trap heat in the atmosphere, which has caused a rapid rise in average global temperatures. Today, the mean global temperature is around 1.1 degrees Celsius warmer than in the pre-industrial era (IPCC, 2019). GHGs emissions are central to many aspects of our industrialized economy, from transportation to electricity generation to agriculture. The environmental consequences of rising temperatures include more frequent extreme weather events, more frequent drought, and rising sea levels. These impacts are already being felt and threaten every aspect of life as we know it, though will disproportionately harm poor, vulnerable communities.

In the face of such an all-encompassing challenge, solutions are also wide-ranging, spanning many sectors including academia, policy, finance, the technology world, and more. Solutions are often categorized as either "mitigation" – strategies that can reduce emissions or remove GHGs from the atmosphere – or "adaptation" – strategies to make the inevitable impacts of climate change more bearable. This dissertation is motivated in general by the desire to address the climate crisis, and more specifically addresses the relationship between agriculture and climate change, and the study of how different uses of land can contribute to or mitigate climate change.

The global agriculture system currently faces several intertwined and opposing challenges. Agriculture, forestry, and other land use activities are major contributors to anthropogenic climate change, responsible for between 21-37% of GHG emissions overall. Additionally, these activities are the leading contributors to methane and nitrous oxide emissions, responsible for 44% of methane, and 81% of nitrous oxide emissions (IPCC, 2019). Greenhouse gas emissions result from all areas of food production systems. Deforestation and peatland degradation due to crop area expansion are a large source of emissions. Methane is emitted via enteric fermentation in ruminant livestock and rice cultivation, and nitrous oxide emissions are exacerbated by the application of excess nitrogen fertilizer. The industrial production of synthetic fertilizers and pesticides, transportation within the food supply chain, the growing popularity of meat-heavy diets, and food waste all further contribute to agriculture's climate impact (IPCC, 2019).

In addition to global climate impact via emissions, agriculture is also responsible for localized environmental harm. The worst excesses of industrialized modern agriculture and poor land stewardship have led to soil erosion, water pollution from fertilizer and pesticide runoff, and harm to human health (Pimentel & Pimentel, 1990; Cordell et al., 2009; Ruane & Rosenzweig, 2018; Rosa et al., 2020). One example, of particular relevance to this dissertation, is nitrogen pollution. Agriculture is the largest source of excess nitrogen in coastal and aquatic ecosystems, which has led to "habitat degradation, alteration of food-web structure, loss of biodiversity, and increased frequency...of harmful algal blooms" (Howarth, 2008). In certain regions, agriculture also puts significant pressure on important and scarce resources, like water, land, and non-renewable resources such as phosphate rock (Fixen & Johnston, 2012; Lambin & Meyfroidt, 2011; Aeschbach-Hertig & Gleeson, 2012).

At the same time, projections of a growing global population with changing dietary preferences suggest that food systems will actually need to produce around 50% more food by mid-century, relative to 2010 (Cleland, 2013). There are additional layers of complexity in the food security conversation: beyond the absolute amount of food needed, food should be equitably distributed, and provide an adequate balance of vitamins and nutrients for the global population (Gómez et al., 2013). For some countries, particularly poor and developing countries that are sensitive to fluctuations in global food pricing, there is a desire to achieve food self-sufficiency; that is, to produce enough calories within their country boundaries to feed their own population. In Sub-Saharan Africa, which is predicted to see a 2.5-fold population increase, and still suffers from relatively high levels of malnutrition, these concerns are particularly acute (Gómez et al., 2013; Van Ittersum et al., 2016). Though food security is not a specific focus of this dissertation, it is mentioned here to illustrate the broad range of complex issues at play in the climate and agriculture space.

Another entanglement of climate change and agriculture is that while food systems contribute to climate change, they are also subject to feedback from the changing climate. Some environmental changes may have a short-term benefit for food production; for example, increased atmospheric carbon dioxide results in higher plant productivity and more efficient water use. Other impacts, such as changes in the number of frost days or the number of hot nights, will benefit some regions and crops, while harming others (Hatfield et al., 2014). Many impacts, however, will have a negative effect, such as more frequent extreme weather events and heat stress (Ruane & Rosenzweig, 2018). Indirect impacts such as sea-level rise, flooding, water stress, and shifting pest zones are likely have to negative impacts on agricultural yields as well.

Taken together, changes in the climate are predicted to alter the geospatial distribution of food production. Warming northern regions that were previously too cold for agriculture will open up to food production, while production may drop in equatorial regions experiencing increased desertification. This redistribution is likely to exacerbate the issue of equitable food access. On the other hand, if this redistribution is accompanied by climate-forward agriculture and land use policies, there is an opportunity to harness these changes to lessen the impact of agriculture on the environment. In a recent analysis, Beyer et al. (2022) model an optimal cropland redistribution that, if non-optimal agricultural areas were to undergo ecological restoration, could decrease the carbon footprint of agriculture by 71%, decrease the negative biodiversity impacts of agriculture by 87%, and reduce the irrigation water footprint by 100%. To mitigate the impacts of agriculture on climate change, while addressing the challenges of food security, it is imperative to consider the environmental implications of agricultural land use, whether that land stays in production, or passes out of production.

For land that stays in agricultural production, there are a plethora of climate-forward solutions that draw on agricultural science, biotechnology, and policy. While these solutions are not the focus of this dissertation, they can provide useful context. In the technology realm, bioengineering efforts are underway to help crops adapt to hotter, more extreme temperature (Ronald, 2011). Sensor-enabled precision agriculture could help farms use scarce resources like water more efficiently (Bogue, 2017). In the policy realm, among other strategies, there are subsidy programs to encourage sustainable practices, and agricultural land zoning rules that prevent agricultural expansion into vulnerable or degraded areas.

Solutions that seek to explicitly address the linked challenges of food security and climate change are broadly categorized under the heading of *sustainable intensification* (SI). SI solutions focus on increasing agricultural yields on existing farmland, and minimizing the expansion of farmland by combining advances in agroecological management, biotechnology, and precision agriculture tools (Tilman, Cassman, Matson, Naylor, & Polasky, 2002). For example, SI might involve targeted use of synthetic fertilizer alongside integrated pest management or practicing rotational, no-till agriculture on fields of genetically engineered crops (Tilman et al., 2002). Many SI solutions are specifically targeted at closing the yield gap – that is, the gap between potential and actual crop production – on agricultural lands in poor and developing countries. While closing this gap could help produce enough food to feed the growing population without significantly expanding agricultural areas, this strategy would require significant increases in the use of nitrogen fertilizer, which can have severe environmental downsides (Tilman, Balzer, Hill, & Befort, 2011).

For post-agricultural land, *ecological restoration* is widely considered an important strategy for mitigating and adapting to climate change as well as protecting biodiversity (Strassburg et al., 2020; Beyer et al., 2022). Ecological restoration involves targeted human interventions to repair degraded environments, rehabilitate native ecosystem function, and support biodiversity (SER, 2002). Restoration encompasses a wide variety of practices including such as erosion control, revegetation, or reintroduction of native species; selection and application of techniques is highly dependent on the restoration site.

Ecological restoration is part of a broader class of climate strategies called *natural climate solutions* (NCS) that aim to mitigate climate change via improved land management, conservation, or restoration. NCS draw on the ability of land to act as a sink in the global GHG cycle, drawing down carbon dioxide through natural processes and storing it in soil and biomass. The natural response of land and land-based processes has offset about 29% of total GHG emissions over the past decade (IPCC, 2019). Though this carbon drawdown is achieved through natural processes, humans can support and enable these processes through techniques such as ecosystem conservation and restoration, afforestation and reforestation, and others (IPCC, 2019). The emissions benefits of NCS can in some cases be realized immediately – as in the case of conservation of high-carbon ecosystems like peatlands and wetlands – or over the course of decades – as in the case of agroforestry and reforestation (IPCC, 2019). While some NCS, such as afforestation, are at odds with growing food, others can be implemented alongside agricultural production. NCS are of particular interest because they tend to be low cost options for reducing atmospheric GHG concentrations, ranging from $10-40 per ton of carbon depending on local conditions (Adams et al., 2021). Additionally, NCS are thought to have significant environmental, economic, and social co-benefits, including preservation of biodiversity, flood protection, and food security.

The relationship between climate change and agriculture is complex: agriculture is a significant contributor to the GHG emissions causing climate change, but agriculture is also impacted in non-linear ways by the changing climate. To feed a growing global population while lessening the detrimental impacts of agriculture will require novel approaches to our food systems that balance food security with reduction of environmental harms and GHG emissions, careful and deliberate land use policy, and integration of NCS and restoration into holistic land management strategy. This dissertation is focused on sustainable land use in agricultural contexts, and in particular, on supporting targeted ecological restoration efforts in post-agricultural areas. Restoration will play a critical role in alleviating the past and future impacts of agriculture on climate change, and must be considered alongside other sustainable agriculture strategies.

2.2 Land Use, Ecosystem Services, and Paying for Natural Capital

At the heart of the relationship between climate change and agriculture is the issue of land use, or how any given area of land is used, whether for agriculture, forest, housing, or something else. Both climate change and agriculture are deeply tied to the land; in fact, agriculture takes up about 40% of the global land surface (Food and Agriculture Organization of the United Nations, 2022). GHG emissions are closely linked to land use: some uses of land, such as forest or wetlands, are major sinks and stores of carbon, while other uses of land, such as industrial uses, tend to contribute to GHG emissions. Deforestation and land degradation due to agricultural expansion are responsible for large historical emissions, and are predicted to be a significant source of future emissions (Houghton & Nassikas, 2017). Thus, the way that land is used, particularly in the context of agriculture, can have a major impact on climate change and the health of natural environments.

Given the importance of land in both contributing to and mitigating GHG emissions, there is significant academic and practical interest in how land is used, the trade-offs involved in different uses of land, and how land owners come to decisions around land-use. Malek et al. (2019) details how individual land owners are frequently driven by a need to maintain their livelihoods, economic considerations like crop demand or profitability, and agricultural policy. Often, individual decision-makers have no financial margin to be able to prioritize environmental concerns over economic needs, so changes in land use, particularly as they relate to agriculture, frequently involve environmental sacrifices in pursuit of individual economic objectives.

At the same time, these individual decision-makers are often driven by underlying political and economic forces (Lambin & Geist, 2006; Lambin & Meyfroidt, 2011). Governments have long used agricultural policy and financial structures to influence what land is used for agriculture and which crops are grown. One example is the United States' biofuel policy, which mandates blending biofuels into gasoline, and has led to a high proportion of the United States corn crop being diverted to ethanol production. This policy has, at times, led to agricultural expansion to support increased corn production, and raised food prices because of competition for corn among biofuels, livestock feed, and human food (Searchinger & Heimlich, 2015).

Historically, economic incentives and motivations have superseded environmental concerns, because detrimental environmental impacts were considered system externalities. For both individuals and governments, when there are few short-term consequences for harming the environment, and few short-term benefits to protecting it, it is easy to make environmentally damaging, but economically profitable land use choices. One way of aligning economic and environmental goals is through the concept of ecosystem services.

Ecosystem services are the services and goods we get from natural ecosystems, such as clean air, soil carbon, and wildlife habitats (US EPA, 2022a). The academic and institutional formalization of this concept is relatively new; the first academic papers on the idea of ecosystem services were published in the fields of environmental and ecological economics in the late 1970s and 1980s (Westman, 1977; Ehrlich & Ehrlich, 1981; de Groot, 1987). There was continued academic interest in the topic throughout the 1990s (Costanza & Daly, 1992; Daily, 1997). The Millennium Ecosystem Assessment (MEA), published in 2005, led to mainstream interest in the idea of ecosystem services and established the following taxonomy of ecosystem services (Millennium Ecosystem Assessment, 2005; Gómez-Baggethun, de Groot, Lomas, & Montes, 2010):

- *Provisioning*: Services such as the provision of food, fresh water, fuel, fiber, and other goods
- *Regulating*: Services such as climate, water, and disease regulation as well as pollination
- *Supporting*: Services such as soil formation and nutrient cycling
- *Cultural*: Services such as educational, aesthetic, and cultural heritage values as well as recreation and tourism

Wetlands, an ecosystem type which is the focus of this dissertation, provide a number of ecosystem services including food provisioning, water purification and waste management, erosion control, habitat provision, aesthetic beauty, and recreation (Russi D. ten Brink P. & N., 2013). Because ecosystem services are not always directly observable, services are usually tied to *ecosystem service indicators*, which “report on the overall status, trends of ecosystems and their values, thereby helping to identify the most urgent environmental problems to address, while also helping to set up the policy priorities" (Russi D. ten Brink P. & N., 2013). Indicators help track and quantify ecosystem services. For example, if a wetland ecosystem performs the service of water purification, the indicator tied to this service might be the percentage of harmful nutrients removed from nearby water. Further examples of wetland ecosystem services and their corresponding indicators are presented in Table 2.1. Notably, most supporting services do not have an easily observable ecosystem service indicator because their impacts on people are "often indirect or occur over a very long time" (Millennium Ecosystem Assessment, 2005).

Type of Ecosystem Service	Ecosystem Service	Ecosystem Service Indicators
Provisioning service	Food e.g. harvested crops, fruit, wild berries, nuts, fish, game	Crop, livestock, or fish production in tons
Provisioning service	Water	Total freshwater resources in cubic meters
Regulating service	Climate regulation e.g. carbon sequestration	Total amount of carbon sequestered and stored
Regulating service	Moderation of extreme events including flood control	Trends in number of damaging natural disasters and probability of flooding incidents
Regulating service	Water purification and waste management	Removal of nutrients by wetlands in tons or percentage
Cultural service	Landscape and amenity values	Changes in number of local residents and real estate values
Cultural service	Ecotourism and recreation	Number of site visitors per year
Cultural service	Cultural and inspirational value	Number of educational excursions at a site or number of scientific publications or patents derived from the site

Table 2.1: Selection of wetland ecosystem services and corresponding indicators (Russi D. ten Brink P. & N., 2013)

In addition to mainstream formalization of the idea of ecosystem services, the MEA also increased focus on identification, quantification, and valuation of ecosystem services. The practice of *ecosystem service valuation* has occasionally attracted controversy, with critics stating philosophical opposition to the "commodification of nature", or suggesting that it doesn't make sense to discuss ecosystem services in economic terms because market forces are often at odds with ecosystem conservation (McCauley, 2006). Nonetheless, in the decades since this criticism, high-level economic models have become more clearly aligned with conservation, and ecosystem service valuation has become a widely used tool in analyzing trade-offs and performing cost-benefit analyses in environmental policy making (Swiss Re Institute, 2021). For example, in 2015 the Obama administration put out a memorandum directing federal agencies to "promote consideration of ecosystem services, where appropriate and practicable, in planning, investments, and regulatory contexts" (Executive Office of the President of the United States, 2015).

More formal processes for quantification and valuation have allowed ecosystems services to be deployed in a wide-range of policy approaches and incentive schemes, which are sometimes called payment for ecosystem services (PES). Some PES take a more top-down approach that involves direct payments or tax benefits for ecosystem services. For example, the USDA's Conservation Reserve Program pays farmers to take environmentally vulnerable land out of production in order to "improve water quality, prevent soil erosion, and reduce loss of wildlife habitat" (USDA Farm Service Agency, 2021). The Environmental Quality Incentives Program is another USDA program that provides financial and technical support to farmers to "deliver environmental benefits such as improved water and air quality, conserved ground and surface water, increased soil health and reduced soil erosion and sedimentation, [and] improved or created wildlife habitat" (USDA NRCS, 2022a). REDD+, a program run by the United Nations, channels payments from high-income countries to lower-income countries to pay these countries to preserve forests (United Nations Framework Convention on Climate Change, n.d.).

In addition to direct payments, PES can also take a more market-based approach. Some well-known examples of ecosystem service markets are cap-and-trade carbon markets, such as the European Union Emissions Trading System. In cap-and-trade markets, the right to pollute is structured as an allowance, and a maximum number of allowances is set as a cap for the system. Within this market, the right to pollute becomes a scarcity, so entities who pollute below their allowance can sell the right to pollute, while entities who cannot reduce their pollution can buy the right to pollute. As the overall number of allowances in the system decreases, the idea is that overall pollution will also decrease. The sulfur dioxide emissions trading scheme, which was created to address acid rain in the 1990s, is considered a very successful example of a cap-and-trade approach to reducing an environmental harm (Ribaudo et al., 2008).

Another market PES paradigm is the voluntary market, in which demand for an ecosystem service, such as sequestered carbon, is driven by buyers who want to reduce or manage their own environmental footprint. For example, retail carbon markets, in which individuals or companies buy carbon credits to become "carbon neutral", are an increasingly popular example of voluntary markets. Recently, voluntary carbon markets have begun to enable conservation of wetlands through the purchase of "blue carbon credits", which recognize and protect the carbon stored in aquatic environments, such as wetlands (Waquoit Bay National Estuarine Research Reserve, 2019; Verra, 2020). Another example is the Wetland Mitigation Banking Program, an offsets market created under Section 404 of the Clean Water Act. In this market, credits are awarded for wetlands in their entirety, not just the carbon they sequester. The program allows landowners to earn credits for creating or restoring wetland, which can then be sold to an entity, often a developer, who wishes to remove wetlands (Waquoit Bay National Estuarine Research Reserve, 2019).

Beyond the Wetland Mitigation Banking Program, there are few markets dedicated to ecosystem services other than carbon storage and sequestration. One, however, is the Ecosystem Services Market Consortium (ESMC), a voluntary market in pilot mode, that specifically seeks to incentivize creation and protection of ecosystem services on agricultural lands (ESMC, 2019). One interesting feature of the ESMC is that it explicitly permits *asset stacking*, which allows participants to receive multiple credits or payments for different services provided by the same parcel of land. Asset stacking can make conservation-focused projects financially viable, and lead to higher-quality project implementations when there is a financial incentive for ecologically holistic thinking (Cooley & Olander, 2011).

PES systems do face a few key critiques and challenges. Some worry that PES focus too much on market development and the commodification of resources at the expense of raising awareness about conservation (Peterson, Hall, Feldpausch-Parker, & Peterson, 2010). Others worry that by creating economic incentives for conservation, PES will supplant community-oriented stewardship of these resources with the advancement of individual economic selfinterest (Gómez-Baggethun et al., 2010). Another recurring critique of PES, particularly voluntary markets, is that they lead to moral hazard situations, in which polluters are emboldened to create further pollution, knowing they can easily and, often, cheaply, "offset" or "erase" their impact. For example, there is concern that companies who plan to become carbon-neutral will do so solely by purchasing offsets instead of committing to internal emissions reductions (Fankhauser & Hepburn, 2010).

PES design and implementation also raise practical challenges and concerns. Chief among these challenges is the difficulty and cost of measuring, monitoring, and verifying the provision of ecological services, which can increase market transaction costs. Ecological services are often difficult to observe, either because they are ephemeral, remote, or spatially diffuse. Additionally, ecosystem changes occur over a protracted timescale that does not always fit with modern market conventions (Ribaudo et al., 2008). The difficulty of ecosystem service measurement can exacerbate uncertainty for both buyers, who need to trust the veracity of the services they purchase, and sellers, who want to be able to estimate how much value they might generate by cultivating ecosystem services (Ribaudo et al., 2008).

On the whole, PES are an immature space: demand-driven, fragmented, and largely unregulated, with few common standards across regions or credit types (Ribaudo, Greene, Hansen, & Hellerstein, 2010). Nonetheless, they are growing in popularity and becoming increasingly standardized. One interesting aspect of PES is that they offer a channel through which citizens, institutions, and organizations can influence and support the production of ecosystem services. In the past few years, for example, several multinational corporations have announced plans to become carbon neutral, which they plan to accomplish through the purchase of carbon credits on voluntary carbon markets (Natural Capital Partners, 2019). The ESMC has attracted participation from a range of visible and powerful corporations – including General Mills, Cargill, Nestle, and The Nature Conservancy – indicating strong interest in the mechanism of ecosystem service payments in a market setting.

At a high level, PES are an important tool for internalizing environmental harms and benefits, which have traditionally been system externalities (Daily & Ellison, 2002). However, ecosystem services are still a relatively young concept, and there is significant work to be done improving ecosystem service mapping, quantification, and valuation (Braat & de Groot, 2012).

Additionally, there is a great need for regional, context-dependent analyses, as sustainable land use depend on “consideration of local environmental and socio-economic conditions” (IPCC, 2019). While this thesis does not make methodological contributions to PES, it draws extensively on the concept of ecosystem services as a way to draw environmental and economic aims into alignment, and presents region-specific estimates for ecosystem service valuation. Situated within the emerging PES landscape, this dissertation is meant to explore the possibility of introducing PES systems in the MA cranberry industry.

2.3 Historic, Economic, and Sociocultural Context of New England Cranberries

Cranberry farming is an agricultural industry that, while small in the broader scope of global agriculture, is experiencing, and is emblematic of, many of the challenges the global agriculture system currently faces. Cranberry farming is historically, culturally, and economically important in New England, particularly southeastern Massachusetts (MA). Cranberries, which are a wetland plant native to the region, were used by indigenous communities for rituals and commerce (Cape Cod Cranberry Growers’ Association, 2021). Active cultivation began in the early 1800’s, when a Revolutionary War veteran noticed that cranberries grew better in a layer of sand. This technique gained popularity, inducing a “cranberry fever” among nearby landowners, many of whom converted their wetlands to cranberry bogs. In addition to the application of a sand layer, other cranberry farming techniques that developed over time included significant alteration of wetland topography and hydrology to control flooding and water flow, and the application of fertilizers, herbicides, and pesticides (K. Ballantine et al., 2020).

In the modern era, cranberries have remained a prominent agricultural product for MA. Cranberry bogs occupy around 13,500 acres in southeastern MA; MA is responsible for 15% of the world’s cranberries, and 31% of US acreage (Massachusetts Department of Agricultural Resources, 2016). Encompassing a number of spinoff industries, such as cultivation, processing, and tourism, cranberry farming generates around $1.4 billion in economic value to the state, making cranberries MA’s most valuable agricultural product. Between on-farm work, processing, and cranberry-related services, the industry provides around 7,000 local jobs, an economic impact which “cascades through the state economy” (Massachusetts Department of Agricultural Resources, 2016).

Southeastern MA is the oldest cranberry growing region in the country, and as such, the cranberry is also culturally important to MA and to the region. Cranberry is the official state berry and color of MA; cranberry juice is the official state drink. There is a yearly “Cranberry Day” event on Martha’s Vineyard and a Cranberry Harvest Celebration in Wareham. Some cranberry farms offer agritourism opportunities, where visitors can experience harvesting berries or cooking demonstrations (Massachusetts Department of Agricultural Resources, 2016).

In recent decades, despite its one-time dominance, the MA cranberry industry has faced significant competition from cranberry farming in the Midwest and Canada, where cheap land and new, hybrid cranberry cultivars have lowered costs and raised yields. In the past decade, Wisconsin and Quebec surpassed MA in terms of total cranberry production. These regions tend to have higher average cranberry yields, due to the large number of MA acres farmed under older, less efficient methods and with lower-yielding native cranberry cultivars. Increased competition and costs, and depressed cranberry prices have meant that as of 2016, many MA cranberry growers were not earning enough to cover their production costs (Massachusetts Department of Agricultural Resources, 2016). Additionally, the cranberry farming population is aging, and there is limited interest among the next generation in continuing to farm cranberries (Abel, 2020).

This confluence of challenges has made cranberry production unsustainable for many MA cranberry farmers. The Cranberry Revitalization Task Force, convened for the first time in 2016 to address these challenges, estimated that up to 40% of cranberry bogs in Massachusetts could be removed from production over the next 10-15 years (Massachusetts Department of Agricultural Resources, 2016). The Task Force focused on two main pathways for farmers: investing in farm renovations and new cranberry vines to lower costs and boost yields, or designing industry exit strategies for farmers that were financially and environmentally viable (Massachusetts Department of Agricultural Resources, 2016). To keep the land in production, some farmers might opt to sell their land to another cranberry farmer, contributing to growing consolidation within the industry. Another option that is considered potentially lucrative is selling land to housing, mining, or alternative energy developers, though this could result in detrimental environmental consequences. Additionally, development on wetlands is restricted under the Wetlands Protection Act, which means that the development potential of cranberry farm bogs is largely tied to adjacent upland (i.e. non-wetland) areas within the same property parcel. Farmers who can't afford farm renovations or don't want to sell their land might opt to simply abandon active production, to avoid the costs of farming.

Another option for farmers that is gaining traction and attention is participating in an active wetland restoration, a process by which man-made farm artifacts are removed from cranberry bogs to allow them to return to their natural wetland state. The cranberry farm restoration process is under active study and is thought to provide significant ecological and social benefits (K. Ballantine et al., 2020). Given the scale of the cranberry industry and the amount of ecologically valuable yet vulnerable land at stake, farmers, local governments, and environmental advocacy groups alike are interested in guiding, understanding, and coordinating what happens to the land currently used for cranberry farming.

2.4 Environmental Context, Wetland Restoration, and the Learning Community

The environmental context of Southeastern MA and the unique ecological history of cranberry farming make wetland restoration particularly compelling. Most cranberry farms in MA were built on top of native wetlands. Wetlands are an important and vulnerable ecosystem, characterized by wet soils that can sustain hydrophytic ("water-loving") plant and animal species. Wetlands and the native species that grow in them perform important ecosystem services, such as filtering water and mitigating floods. With their waterlogged soils, wetlands are also able to store a significant amount of carbon and water due to the slow decomposition of organic matter in anaerobic conditions. These areas provide crucial habitats and breeding grounds for wildlife and fish, and are a backdrop for human recreational activities. Unfortunately, despite their ecological importance, wetlands are vulnerable to development for agriculture and housing; indeed, MA lost 28% of wetlands due to human activity—including cranberry farming—between 1780 and 1980 (Dahl, 1990).

Though there is nuance, the environmental impacts of cranberry farming have generally been detrimental to native ecosystem function and natural resources. Cranberry farms require intensive water management and often involve the addition of sand to promote root aeration, which can alter soil conditions and disturb native habitats. Cranberry farming is highly water intensive and, due to the application and runoff of nitrogen- and phosphorus-based chemical fertilizers and pesticides, can threaten water quality in the surrounding watersheds (Hoekstra, Neill, & Kennedy, 2019; Kennedy, Buda, & Bryant, 2020). On the other hand, cranberry vines are perennial plants that store carbon in their root systems; because bogs are not tilled, it is likely that cranberry bogs are a net carbon sink (Gareau, Huang, & Gareau, 2018). Growers often manage acres of natural uplands in the vicinity of their fields, which support natural flooding of the cranberry bogs, provide informal recreation areas, and create a buffer between agricultural areas and other land uses (A. Hackman, personal communication, August 9, 2021). Thus, while cranberry bogs are monocultures, they are often situated within, and depend on, the broader context of a diverse ecological area (Gareau et al., 2018).

It is important to situate the impacts of cranberry farming and questions around cranberry bog land use within the context of environmental challenges in the broader region. In Southeastern MA, excess amounts of nitrogen and phosphorus pose a major threat to clean drinking water and aquatic ecosystems such as estuaries and freshwater ponds. Though nitrogen and phosphorus occur naturally in the environment, human activities can lead to excess quantities of these nutrients in waterways, which "contribute to algae blooms; low dissolved oxygen; degradation of seagrass; impaired freshwater and estuarine ecosystems; and, in extreme cases, fish kills" (US EPA, 2022b). Nitrogen and phosphorus pollution are a major challenge in Southeastern Massachusetts, largely due to widespread septic systems and fertilizer application for agricultural and recreational uses. Restoring cranberry farms to wetlands is thought to address the challenges of excess nutrient leaching and improve water quality in two ways: first, when cranberry farms are restored to wetlands, nutrient-rich fertilizer would no longer be applied to these areas on a yearly basis for agricultural purposes; and second, wetlands are able to absorb some of the excess nutrients transported by groundwater, and prevent these nutrients from reaching rivers and bays in the watershed. Given these environmental considerations, and the industry challenges described in the prior section, there is significant interest in the possibility

Figure 2-1: Operational Cranberry Farm (Glorianna Davenport)

Figure 2-2: Cranberry Farm Post Restoration (Kristin Foresto)

of restoring retired cranberry farms to their native wetland state.

Over the past decade, the MA Department of Fish and Game's Division of Ecological Restoration (MA DER) has partnered with with diverse federal and local entities to undertake four cranberry bog restorations in Southeastern MA: Eel River in Plymouth (completed 2010), Tidmarsh Farms in Plymouth (completed 2016), Coonamessett River in Falmouth (2018 and 2020), and Foothills Preserve in Plymouth (nearing completion at the time of writing) (K. Ballantine et al., 2020). The goal of these restorations is to rehabilitate native ecosystem function and remove man-made artifacts. For cranberry bogs, restoration often includes removing or roughing up the sand layer (farmers usually apply 1-3 inches of sand every few years to help with weed control), construction of a stream channel, removal of dams and other water control structures, and the planting of native trees and shrubs. The contrast between an operational cranberry farm and a post-restoration wetland can be seen in Figures 2-1 and 2-2.

Some of the MA DER's partners have included the USDA Natural Resources Conservation Service (NRCS), land trusts, local municipalities, non-profits, the Cape Cod Cranberry Growers' Association, and others. Because wetland restoration of cranberry-farms is a relatively new undertaking, these projects have served as the basis for an "innovative, scientifically-informed, process-based approach to restoring cranberry farmland to self-sustaining wetlands" (K. Ballantine et al., 2020). In 2020, the MA DER won a $10 million grant from the NRCS' Regional Conservation Partnership Program, which will allow them to apply these methods to another 20 projects over the next five years, restoring another 900 acres of high-value wetlands (USDA NRCS, 2022b).

Alongside MA DER's restoration activities, a diverse research community has come together to learn from and guide these restoration projects. Living Observatory (LO) is a "public interest learning collaborative of scientists, artists, and wetland restoration practitioners engaged in the documenting, interpreting, and revealing the arc of change as it occurs prior to, during, and following the ecological wetland restoration on retired cranberry farms" (Living Observatory, 2021). Originally founded in 2011 to track the Tidmarsh Farms restoration, LO formally incorporated as a non-profit in 2015, and widened its scope to focus broadly on cranberry farm restorations in the region. Their mission and goals, which are reproduced in full in Appendix A, are to tell the story of ecological restoration on cranberry farms via scientific and socioeconomic research, long-term ecological monitoring, and interdisciplinary collaboration (Living Observatory, 2021).

As part of LO, my research lab, the Responsive Environments Group at the Media Lab, has had the opportunity to conduct unique multidisciplinary research at the Tidmarsh restoration site over the past decade. Beginning around 2013, our group instrumented the 600-acre Tidmarsh site with a custom low-power sensor network and communications infrastructure that gathered data on soil moisture, temperature, humidity, and more (B. Mayton et al., 2017). This sensor network was accompanied by multiple audio capture installations that supported real-time live streaming (B. D. Mayton, 2020). The purpose of these sensing and audio networks was to monitor ecological change during the restoration, as well as provide a novel platform for people to interact with the changing landscape. For example, data from the sensing nodes was used to understand how soil moisture varied across the site before, during, and after various restoration techniques (B. D. Mayton, 2020). In another project, called Doppelmarsh, data from the sensing network was leveraged to create a virtual reality version of the Tidmarsh wetland, so that people could explore and interact with data in realtime (Haddad et al., 2017). The HearThere project involved the development of an auditory augmented reality experience in which a listener wore bone conduction headphones that layered sounds from the Tidmarsh ecosystem on top of their natural hearing experience (Dublon, 2018).

In the broader LO community, there has been diverse research on the ecological impacts of restoring cranberry farms to wetland habitat. Bartolucci, Anderson, and Ballantine (2020) studied greenhouse gas fluxes on different types of post-farming bogs, including young and old retired (but not restored) cranberry bogs, young and old restored wetlands, and a natural reference bog. They found that emissions differed significantly by site type, and that the older restoration site had lower emissions than the newly restored site, suggesting that over time, restored wetlands may become net greenhouse gas sinks. In a different study, K. A. Ballantine, Anderson, Pierce, and Groffman (2017) found that restoration helps rebuild soil organic matter and soil moisture, which in turn increases the potential for denitrification, a microbial process that can mitigate water pollution. Overall, restoration is thought to be likely to reduce nitrogen and phosphorus concentrations in the surrounding watershed, not only because restoration removes the source of these contaminants, but also because wetlands can remove these nutrients through plant uptake and denitrification (Land et al., 2016). Another study found that restored wetlands had higher faunal diversity—including native amphibians and reptiles, rare birds, and fish—compared to retired but not restored cranberry farmland (Christen et al., 2019). While there is still scientific research to be done to specify the exact impacts of these cranberry bog restorations, there is overall consensus that the process helps rebuild wetland ecosystem functions, increases resilience to climate change, and improves habitat diversity and complexity. These benefits would be particularly compelling in the context of Southeastern MA given local environmental conditions.

2.5 Research Gaps and Opportunities

The research described in this dissertation is inspired and informed by the activities, guidance, and collective knowledge of LO and prior Responsive Environments work at the Tidmarsh restoration site. Building on the technological infrastructure and scientific discovery advanced over the past decade around ecosystem services from wetland restoration, this dissertation applies the concept of PES to the region, conducting an analytical case study of the potential benefits of restoration.

This work aims to fill a knowledge gap around the regional distribution and value of wetland-related ecosystem services, using models to extrapolate and layer the scientific research that has been ongoing at wetland restoration sites. Wetland restorations are expensive and require stakeholder alignment. Thus, another broad aim of this dissertation is to, using the concept of PES, identify synergies between environmental and economic outcomes of restoration in order to identify priority areas for restoration and make an economic argument for wetland restoration in the region. Finally, another gap this work addresses is the availability of data-driven tools connecting on-the-ground scientific research with decision-makers. By creating accessible, user-friendly tools and developing information, this dissertation aims to support decision-makers and restoration practitioners in the region.

Chapter 3

Methodological Framework

This dissertation integrates tools from diverse disciplines to perform an assessment of ecosystem services under different land use scenarios in the MA cranberry industry. First, I draw on systems engineering methods which are frequently used for sustainable development to gather relevant socioeconomic and political context from the region. I use this context to guide and structure an ecosystem services analysis. Then, I use methods and models from environmental economics and geospatial analysis to analyze the impact of land use on different ecosystem services. Finally, I draw on best practices in geospatial data visualization and usability research to design, develop, and evaluate a web-based data exploration tool that presents the results of the modeling analysis in a user-friendly format. This chapter will briefly introduce the methodological framework of the dissertation and provide information about how and why certain methods were selected.

It is important to note that Section 3.1, which introduces the history and background of Systems Engineering and its application to Sustainable Development, is adapted from a review paper written by Jack Reid that is currently under review. Many of the methodological choices presented in this section were developed in collaboration with the EVDT working group at the MIT Media Lab during the 2021-2022 academic year.

3.1 Systems Engineering Approaches to Sustainable Development

Systems engineering encompasses a wide array of tools, methods, and models for designing and managing complex systems. Complex systems are systems with multiple layers of complexity, each consisting of different components, and multiple stakeholders who must navigate complex social, environmental, and economic interrelationships. Complex systems often exhibit emergent behavior that results from interactions between system components, and may produce unintended consequences, generate nonlinear behavior, or demonstrate shifting dynamics that create tipping points. Stakeholders operating within these systems often must make decisions under uncertainty, satisfying diverse constraints and objectives (Rechtin & Maier, 2010; de Weck, Roos, Magee, & Vest, 2011; Sterman, 2012).

Systems engineering originated in the 1950s as a means of managing complexity in traditional engineering projects in aerospace and transportation. In the 1960s and 1970s, systems engineering methods were used in urban planning and development settings, with mixed results due to the inability of some models to capture the complexity of urban social issues (Lee, 1973). In the past several decades, systems engineering has come to encompass a more holistic approach that strives to integrate not only the physical constraints of systems, but also the socioeconomic and political context of a system (Te Brömmelstroet & Bertolini, 2010).

More recently, there have been efforts to apply the methods of systems engineering to challenges in sustainable development. Sustainable development was originally defined as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (Visser & Brundtland, 2013). Sustainable development involves managing the tradeoffs, and discovering synergies between economic growth, social objectives and social justice, and environmental protection, as in Figure 3-1 (Campbell, 1996). In 2015, the United Nations (UN) published the Sustainable Development Goals (SDGs) as part of their 2015-2030 agenda. The SDGs set priorities and targets for different aspects of sustainable development in the global development agenda (The General Assembly of the United Nations, 2015).

Given the complexity of sustainable development aims, many feel it is an appropriate ap-

Figure 3-1: "The Planner's Triangle" Adapted from Campbell (1996) via Jack Reid

plication area for systems engineering approaches, especially methods that take into account the needs and objectives of multiple stakeholders (Campbell, 1996). Several systems engineering frameworks have been applied to work in sustainable development, including socio-environmental systems (SES) and the Stakeholders, Problem, Alternatives, Decision-making, Evaluation (SPADE) methodology (Honoré-Livermore, Birkeland, & Haskins, 2020; Haskins, 2008).

Several members of the Space Enabled Group at the Media Lab have used the *Systems Architecture Framework* (SAF), adapted from Rechtin and Maier (2010), combined with the *Environment-Vulnerability-Decision-Technology* (EVDT) integrated modeling framework, to address challenges in sustainable development (J. B. Reid & Wood, 2020a; Ovienmhada et al., 2020). In general, SAF has been used to establish system context, identify stakeholders, and develop a qualitative understanding of how new technologies, programs, or organizations would impact a complex system. Building on the findings of SAF, EVDT provides a framework for more quantitative analysis, guiding the integration of models that capture information about the physical environment, the socioeconomic needs of stakeholders, their decision-making, and the data and technologies that underlie and support the system. Following the example of others in Space Enabled, this dissertation uses SAF and EVDT to inform and design an analysis of the MA cranberry industry. These methods were a good fit for the study area due to their ability to capture the needs and integrate the perspectives of a wide diversity of stakeholders. The subsequent sections will provide more information on the implementation details of these specific frameworks.

3.1.1 Systems Architecture Framework

The *Systems Architecture Framework* (SAF) is a systems engineering framework used to identify and analyze key characteristics of a complex sociotechnical system. Here, "architecture" refers to an "abstract description of the entities of a system and the relationships between those entities" (Crawley et al., 2004). This framework, visually represented in Figure 3-2, is a method from systems engineering for identifying, describing, modeling, and understanding complex sociotechnical systems. This framework has been applied in a wide array of development, technology, environmental, and health contexts (Wood, 2012, 2013; Ovienmhada et al., 2021; Kazansky, Wood, & Sutherlun, 2016; Joseph & Wood, 2021; Crawley, Cameron, & Selva, 2015). Ovienmhada et al. (2021) argue for using the SAF in complex sustainable development settings because it "emphasizes understanding the organization of processes and relationships in an enclosed system, while maintaining an open and inclusive approach to knowledge generation and valuation." Following this rationale, and drawing on the use of the SAF in a number of structurally similar case studies, I elected to use the SAF to conduct contextual analysis for the MA cranberry industry setting.

As presented and described by Wood (2012) and Rechtin and Maier (2010), SAF analyzes a sociotechnical system by iteratively asking the following questions:

- *What is the system context?* The system context may involve technological, regulatory, economic, environmental, cultural, social, and geopolitical factors that occur outside the defined system boundary, but that might influence what happens within the system.
- *Who are the primary, secondary, and tertiary system stakeholders?* In the language of SAF, primary stakeholders are the stakeholders making decisions that shape and influence the system itself, while secondary stakeholders can influence the decisions of primary stakeholders through information and tools. Tertiary stakeholders do not influence primary

stakeholders, but are impacted by the outcomes of their decisions.

- *What are the stakeholders' needs, desired outcomes and objectives?* In other words, what problems are stakeholders facing? What would they like the world to be like in the future? What can or does the system do to contribute to stakeholders' desired outcomes? It is important to note that stakeholder needs are unique to each stakeholder, while objectives are specific to the system.
- *What functions does the system perform?* Functions are the "activities that transform [system] forms in order to meet objectives" (Wood, 2021)
- *What forms do those functions take?* Forms are "organizations, people, physical or virtual objects, programs and processes that execute functions" (Wood, 2021)
- *How do system functions and forms perform, operate, and change over time?* This analysis may involve observations of how the system forms respond to changes or disruptions, or arguments for and against different possible functions and forms of the system.

In the setting of my case study of the MA cranberry industry, I collected data through a series of stakeholder interviews and a literature review. To apply the SAF, I used a set of graphical tools which were developed via multiple previous case studies. These graphical "templates", developed and presented by Wood (2021), provided a flexible visual structure that allowed me to organize, analyze, and present my data according to the questions above. A selection of these templates are presented in Figures 3-3 and 3-4. In particular, the stakeholder analysis I present draws on the Stakeholder Value Mapping method, drawn from Cameron et al. (2008), which first develops input–output models for each stakeholder and then aggregates these individual stakeholder models into a network. The selection of these methods was based on other academic implementations of the SAF, including Wood (2012), Ovienmhada et al. (2021), and Lombardo et al. (2022), among others.

3.1.2 The EVDT Integrated Modeling Framework

After using the SAF approach to qualitatively describe and understand a complex system, I used the Environment-Vulnerability-Decision-Technology (EVDT) framework to design a

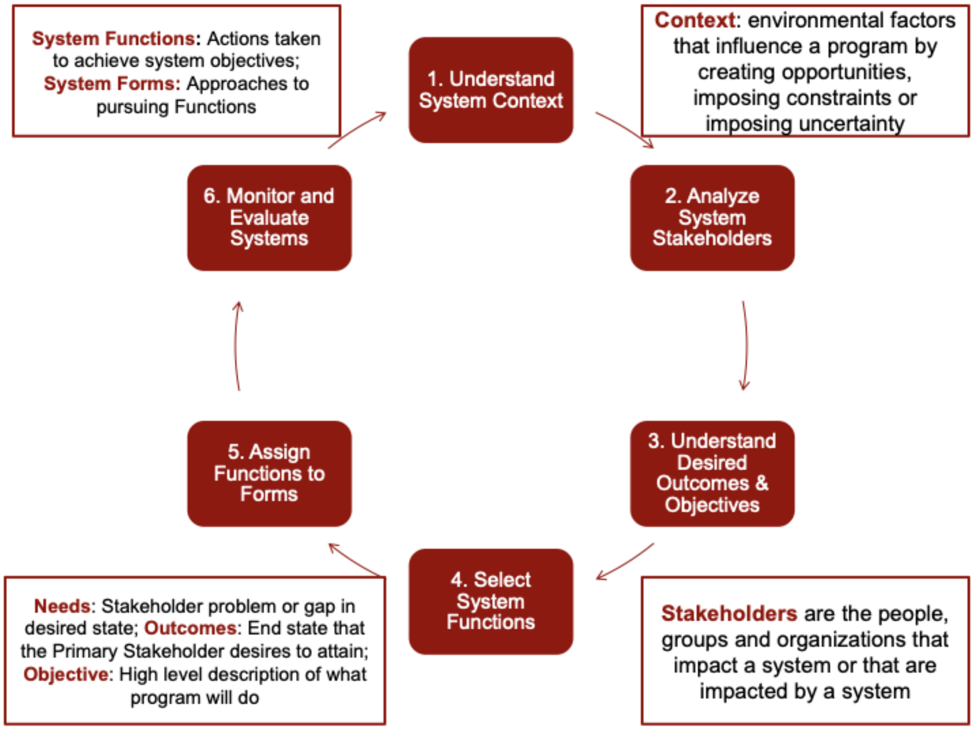


Figure 3-2: Visualization of the Systems Architecture Framework (Wood, 2021; Ovienmhada et al., 2021; Joseph & Wood, 2021)

quantitative, data-driven analysis of the system. EVDT is an integrated modeling framework that was developed in the Space Enabled Group at the Media Lab, and is an approach that aims to capture the feedback loops and interactions of complex systems to guide sustainable development (J. Reid, Zeng, & Wood, 2019).

The EVDT framework "combines modeling capability…from earth science, social science, complex systems modeling of human behavior, and systems engineering models of technology designs" (J. B. Reid & Wood, 2020a). Relative to other integrated modeling frameworks, EVDT is unique in providing the ability to consider environmental and social factors in "multi-stakeholder, high uncertainty contexts" (J. B. Reid & Wood, 2020a).

The EVDT framework is meant to be customizable to the user's application of interest. The baseline framework, presented in Figure 3-5, centers on four submodels, which each ask a key question that drives analysis:

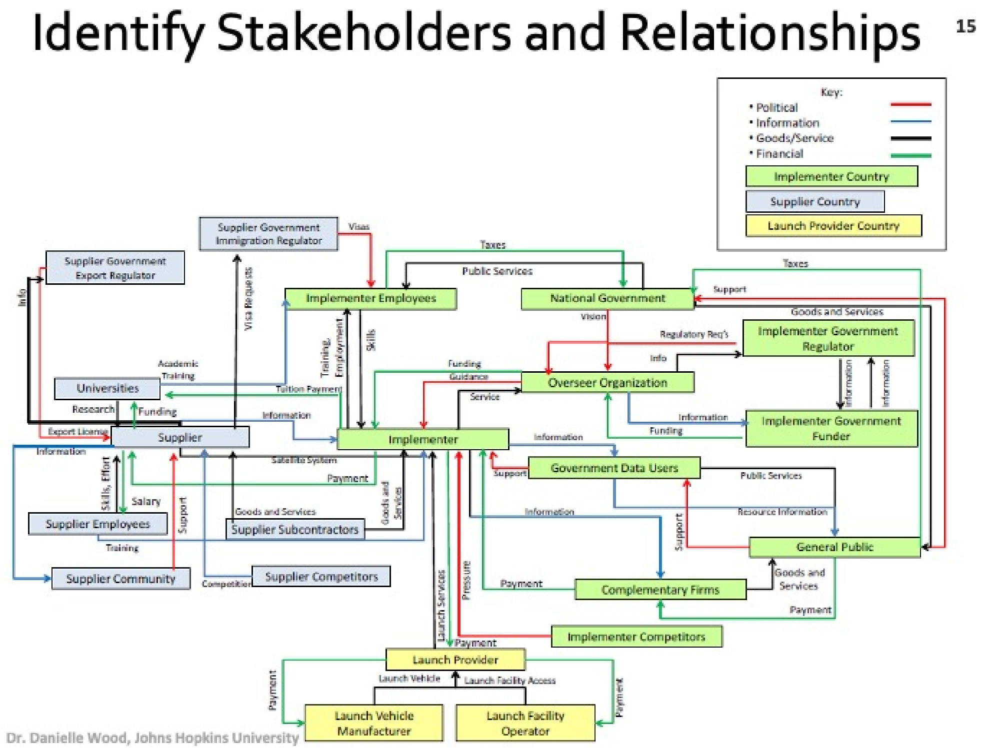
- The Environment model asks, "What is happening in the natural environment?" This model uses earth science, as well as other available environmental sensing data to esti-

Figure 3-3: Graphical Template for Analyzing and Presenting System Context (Wood, 2021)

mate the state of relevant environmental phenomena.

- The Vulnerability model asks, "How will humans be impacted by what is happening in the natural environment?" This Vulnerability Model uses a variety of analysis techniques from engineering and social science to understand how humans are impacted by the state of the environment, as represented by the Environment Model. Some of the approaches used to capture these socioeconomic impacts include ecosystem service modeling, econometrics, and risk analysis, among others.

- The Decision Model asks, "What decisions are humans making in response to environmental factors and why?" In some EVDT implementations, agent-based modeling and discrete event simulation are used to simulate the behavior of a human decision maker. Another approach used in some EVDT implementations is to present the analysis from the Vulnerability model in an interactive tool or game-like interface, which allow users to explore potential outcomes of decisions.



Identify Stakeholders and Relationships 15

Dr. Danielle Wood, Johns Hopkins University

Figure 3-4: Example of Graphical Template for Analyzing and Presenting System Stakeholders (Wood, 2021)

- The Technology Model asks, "What technology system can be designed or acquired to provide high quality information that supports human decision making?" The Technology Model can be a more traditional parametric engineering model that specifically addresses the design of the technical systems used to generate data for analysis in other parts of the EVDT framework. One potential outcome of the Technology Model is to identify new approaches for data collection to meet the data needs of the the Environment and Vulnerability Models.

The EVDT framework can be used in descriptive, evaluative, or decision-support mode. In descriptive mode, the framework simply seeks to accurately capture the different components of a complex system in a quantitative, data-driven framework. In evaluative mode, EVDT can be used to better understand the dynamics of a past decision, or simulate future scenarios. Finally, in decision-support mode, the framework is built out to facilitate interactive stakeholder decision-making.

EVDT provides a structure for combining different submodels that describe environmental and socioeconomic factors, human decision-making, and the technology and information systems that guide and inform the other models. In this dissertation, I use EVDT to design and organize my analysis, guiding the choice of which submodels to use, and what data to incorporate. Among other applications, the EVDT framework has been used to inform management of mangrove forests in Brazil, manage invasive plant species in Benin, and support coastal communities at risk of flooding and land subsidence in Indonesia (J. B. Reid & Wood, 2020b; Ovienmhada et al., 2020; Lombardo et al., 2022). During the Covid-19 pandemic, the EVDT framework was adapted to provide dynamic public health information and guidance; this adaptation of EVDT is called the *Vida Decision Support System* (J. B. Reid, Lombardo, Turner, Zheng, & Wood, 2021). These diverse case studies, with the addition of this dissertation, illustrate the wide range of application areas for the EVDT framework, and demonstrate the viability of using the EVDT framework to address sustainable development challenges across a variety of regions and application spaces.

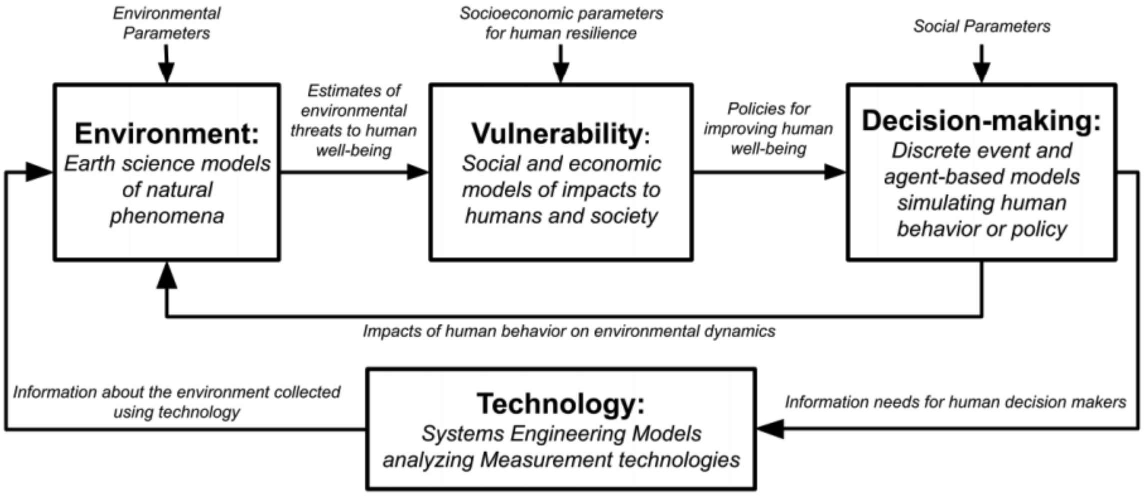


Figure 3-5: Visualization of the EVDT Framework (J. B. Reid & Wood, 2020a)

3.2 Ecosystem Service Modeling and Valuation

EVDT provides a framework for uniting the outputs of various submodels. For the Environment and Vulnerability submodels, I wanted to estimate the amount, distribution, and value of ecosystem services under different land use scenarios in the Southeastern MA. To do so, I drew on the field of ecosystem service modeling and valuation.

Ecosystem service modeling refers to a wide array of models and techniques that integrate scientific data and biophysical processes to generate estimates of the amount and distribution of ecosystem services. *Ecosystem service valuation* goes one step beyond ecosystem service modeling by estimating the value of ecosystem services. Value can be expressed in qualitative or quantitative form; within quantitative valuations, it is possible to have monetary and non-monetary valuations. Using the example of water purification, the qualitative value of water purification might be a description of which communities benefit from that service; a non-monetary quantitative value might express the number of people who benefit from the service; and a monetary quantitative value might capture the avoided costs of building a man-made filtration system (Russi D. ten Brink P. & N., 2013). Traditionally, however, ecosystem service valuations have focused on assigning a monetary value to ecosystem services.

The Total Economic Value (TEV) framework is one of the most widely-used and well-known frameworks for approaching and describing different aspects of ecosystem value. Within TEV, a distinction is made between *use values* and *nonuse values*. *Use values* are "associated with current or future (potential) use of an environmental resource by an individual, while nonuse values arise from the continued existence of the resource and are unrelated to use" (Natural Research Council, 2004). For example, *nonuse values* can include existence value (the benefit people receive simply from knowing that an ecosystem exists), bequest value (the value people place on maintaining and preserving a resource for future generations), and option value (the value someone might place on knowing that a resource would be available for use in the future). *Use values* can be categorized as consumptive or nonconsumptive; within nonconsumptive *use values*, there is a further distinction between *direct* and *indirect* value. These categorizations, which are visualized in Figure 3-6 within the larger context of ecosystems and human actions, all depend on the nature of humans' interactions with an ecosystem and the services it provides.

There are many approaches to ecosystem service valuation within the TEV framework. Some of the more well-known methods, with the most applicability to this dissertation, include: replacement cost, avoided costs, market value, and willingness-to-pay. The replacement cost method involves valuing ecosystem services according to the "next-best alternative means

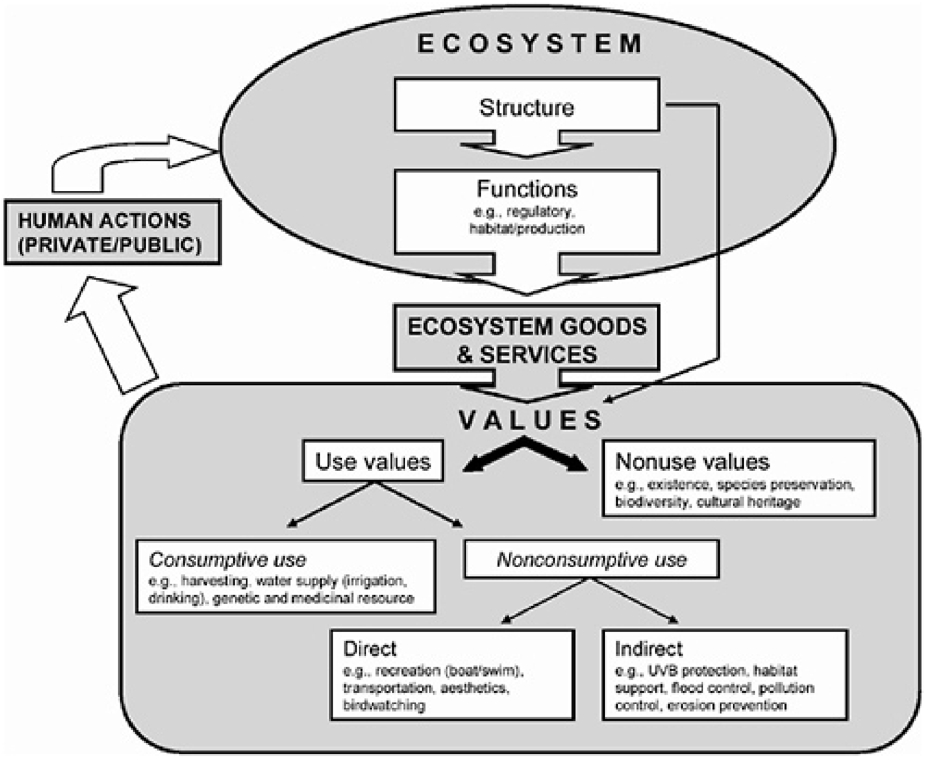


Figure 3-6: Connections between ecosystem structure and function, services, policies, and values (Natural Research Council, 2004)

of providing the required service" (Natural Research Council, 2004). For example, in the case of a watershed that could provide a certain level of nutrient removal, the replacement cost would be the cost of building a man-made water filtration or treatment plant. The avoided cost method involves estimating the value of property protected by an ecosystem. For example, in the case of a watershed that could provide flood mitigation, the value of the watershed might be equal to the cost of avoided property damage to properties in the area.

The market value method is often used in the context of provisioning services, and involves using current market pricing to place a value on the goods provided by an ecosystem. For example, market value could be used to establish the ecosystem service value of a landscape that produces cranberries or stores and sequesters carbon. The willingness-to-pay method involves polling individuals to understand the amount of time or money they would spend to preserve a natural area, and using this amount as a proxy for the value of the natural area (Russi D. ten Brink P. & N., 2013).

These methods represent just a few of the diverse approaches to ecosystem service valuation, which is an area of active economic research (Vo, Kuenzer, Vo, Moder, & Oppelt, 2012; Cheng, Van Damme, Li, & Uyttenhove, 2019). Another important component of monetary valuation is considering how ecosystem services and values will change over time; the aggregated value of the services over time, as well as the potential for the availability of the services to decline, should be factored into valuation-driven policy decisions (Natural Research Council, 2004). To do so, ecosystem service valuation methods often incorporate a discounting rate which "reflects the fact that people typically value immediate benefits more than future benefits due to uncertainty and assumed economic inflation over time" (Sharp et al., 2020).

While ecosystem service valuation has traditionally emphasized utility, rational choice, and monetary valuations, more qualitative, socio-cultural approaches have gained traction in recent years. Scholte et al. (2015) distinguish between "cultural ecosystem services"—defined by the MEA as "services related to spirituality and religiosity, recreation and ecotourism, aesthetics, inspiration, education, sense of place and cultural heritage"—and "socio-cultural values" of ecosystem services, which may be qualitative, and are dependent on social context, age, gender, income, political orientation, and other personal characteristics (Scholte et al., 2015). They review and evaluate methods for socio-cultural valuation of ecosystem services, finding that common methods include: observation, document research, expert-based approaches, questionnaires, and in-depth interviews (Scholte et al., 2015). In a similar vein, Mavrommati et al. (2017) introduced a democratic, community-based approach to valuation in which community members performed a deliberative multicriteria evaluation of natural resources in their area.

3.2.1 Selection of InVEST for Ecosystem Service Modeling

There are a variety of different modeling, valuation, and mapping tools for ecosystem services, each with different strengths and weaknesses. As part of my dissertation work, I evaluated different ecosystem service modeling tools and selected a modeling platform that was a good fit for my analysis. Ecosystem service modeling is an area of active research and I was able to rely on several comparative analyses to narrow down my options. For example, Bagstad et al. (2013) compare 17 different ecosystem modeling tools across different evaluation metrics, which provided useful guidance on selecting an ecosystem service modeling tool.

Drawing from Bagstad et al. (2013), I was able to select three popular and well-known ecosystem service modeling tools to serve as the starting point for this selection process: Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST), Artificial intelligence for Ecosystem Services (ARIES), and Land Utilisation Capability Indicator (LUCI) (Sharp et al., 2020; *ARIES Integrated Modelling*, 2022; *LUCI: Land Utilisation Capability Indicator*, 2018). Jackson et al. (2017) used InVEST, ARIES, and LUCI to analyze nutrient retention, carbon sequestration, and water supply for a study area in the United Kingdom. They found that all the models produced similar outputs, but were optimized for different geographical areas and land use types. ARIES was noted to have more of a predictive approach when data was scarce. Ochoa and Urbina-Cardona (2017) find that InVEST was the most commonly used ecosystem service modeling tool starting in 2009.

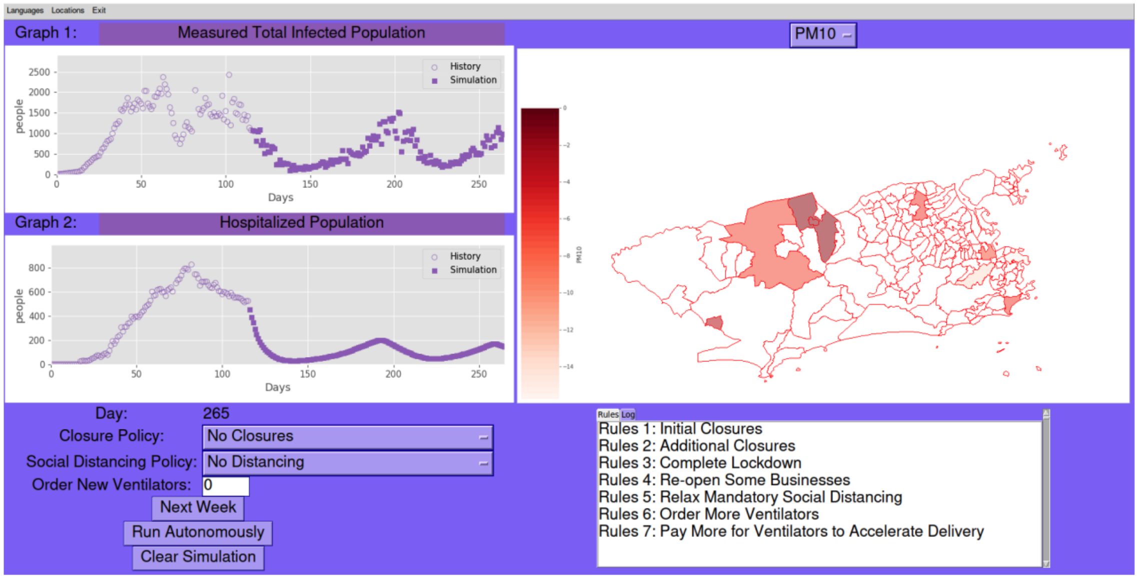
Our team contacted the LUCI team in Fall 2021 to request access to their tool, and did not receive a reply. While ARIES has an active community and publication environment, it was not clear that ARIES provided modeling tools for the ecosystem services most relevant to our study area, including nitrogen and phosphorus mitigation. Based on our review of these options, InVEST, which is freely available, widely used, well-supported, and well-documented, was determined to be the best ecosystem service modeling tool for this dissertation research. Additionally, InVEST is designed to have relatively low data requirements, to work anywhere in the world, and to produce spatially-explicit outputs, which made it a good fit for this work.

3.3 Geospatial Data Visualization Tools

With the advent of more accessible geospatial data, there have been a profusion of mapping tools and geospatial data visualization applications and websites. Here, I highlight two geospatial data explorers from which I drew specific insights in designing a web-based data tool for stakeholders.

The first, presented in Figure 3-7, is a prototype version of an EVDT desktop-based user interface developed by Jack Reid in the Space Enabled research group. EVDT was originally developed as a broad and flexible framework for sustainable development applications (J. Reid et al., 2019). An important element of some EVDT implementations is a user interface that allows users to explore and analyze the outcomes of potential decisions. In 2020, the EVDT framework was refashioned to address the Covid-19 pandemic, which expanded the application space for the framework (J. B. Reid & Wood, 2020a). The expanded EVDT framework, called the *Vida Decision Support System*, allowed public health officials and community leaders to explore, for example, epidemiological data alongside quarantine policies. Figure 3-7 shows an example of the EVDT user interface in use as a Covid-19 policy explorer; the interface allows users to explore the impacts of different Covid-19 lockdown policies in Rio de Janeiro. Two design principles drawn from this example are the focus on geospatial visualization, and the ability for users to explore and subsequently envision the modelled outcomes of different policies and scenarios.

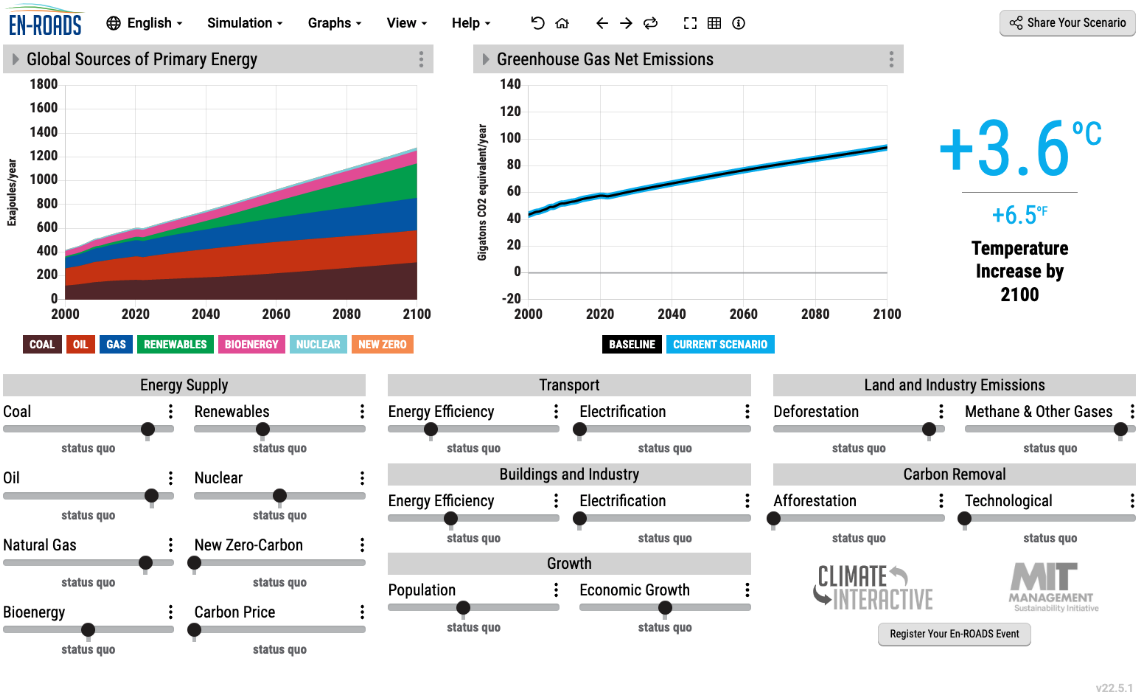
The second data explorer, presented in Figure 3-8, is the En-ROADS climate simulator, developed at the MIT Sloan School of Management (Climate Interactive, 2022). En-ROADS is a educational climate tool, often used to facilitate workshops, that allows users to learn about climate risk through an interactive experience simulating different climate mitigation and adaptation policies in a web application. Though En-ROADS does not visualize geospatial data, it is particularly notable for offering a seamless, user-friendly front-end to complex back-end simulations. Thus, two design principles drawn from En-ROADS are: first, the focus on interactive scenario planning; and second, the responsive and dynamic nature of this site: as the user drags sliders around, the data visualizations in the top half of the site adjust instantly to reflect the updates.



Day: 265
Closure Policy: No Closures
Social Distancing Policy: No Distancing
Order New Ventilators: 0

Rules 1: Initial Closures
Rules 2: Additional Closures
Rules 3: Complete Lockdown
Rules 4: Re-open Some Businesses
Rules 5: Relax Mandatory Social Distancing
Rules 6: Order More Ventilators
Rules 7: Pay More for Ventilators to Accelerate Delivery

Figure 3-7: Screenshot of EVDT Desktop User Interface for Exploring Covid-19 Lockdown Policies (J. B. Reid & Wood, 2020a)



Coal: status quo
Renewables: status quo
Oil: status quo
Nuclear: status quo
Natural Gas: status quo
New Zero-Carbon: status quo
Bioenergy: status quo
Carbon Price: status quo
Transport Energy Efficiency: status quo
Transport Electrification: status quo
Buildings and Industry Energy Efficiency: status quo
Buildings and Industry Electrification: status quo
Population: status quo
Economic Growth: status quo
Deforestation: status quo
Methane & Other Gases: status quo
Afforestation: status quo
Technological: status quo

Figure 3-8: Screenshot of En-ROADS Climate Simulator (Climate Interactive, 2022)

Chapter 4

A Systems Architecture Analysis of the MA Cranberry Industry

4.1 Project Overview

The goal of this portion of the thesis was to conduct a systematic analysis of the Massachusetts cranberry industry to uncover relevant system context, identify different system stakeholders, and understand their needs and objectives. This analysis treated the MA cranberry industry as a complex sociotechnical system, and utilized the *Systems Architecture Framework* (SAF) to structure knowledge collection, which was achieved through stakeholder interviews and a literature review. The contributions of this work include a stakeholder mapping, an analysis of the key needs and objectives of system stakeholders, and discussion of how different system interventions could achieve these needs and objectives. Additionally, the analysis from this portion of my dissertation guided subsequent modeling work (see Chapter 5) and the development of geospatial data visualization tools (see Chapter 6) in latter portions of the thesis research.

4.2 Research Questions

This portion of the thesis research was driven by the following research questions:

- R1: What is the "architecture" of the MA cranberry industry? (Here, "architecture" refers to an “abstract description of the entities of a system and the relationships between those entities” (Crawley et al., 2004))

  - R1.1: Who are the most important decision-makers and key stakeholders in the system?
  - R1.2: What are these stakeholders’ needs and objectives and how does the system achieve (or fail to achieve) these objectives?
  - R1.3: What initiatives, information, activities, or technologies could help stakeholders achieve their objectives more effectively?

- R2: Which environmental, economic, and social factors are most important to industry and regional stakeholders?

4.3 Research Design and Methods

To address the above research questions, I applied the *Systems Architecture Framework* (SAF) in the context of the MA cranberry industry. The selection of SAF, and the individual methods used to implement SAF, was based on other academic case studies on sustainable development, including Wood (2012), Ovienmhada et al. (2021), and Lombardo et al. (2022), among others. I collected data through a series of stakeholder interviews and a literature review, then applied the SAF to this data, primarily through the use of a set of graphical "templates" which were developed and disseminated by Wood (2021), as well as the Stakeholder Value Mapping method (Cameron et al., 2008). These methods allowed me to uncover insights about the relationships between stakeholders and their needs in the context of the MA cranberry industry system, which in turned influenced the design and focus of subsequent research presented in this dissertation. Additionally, I used qualitative coding methods to analyze stakeholder responses and relevant literature to select environmental factors for further analysis and modeling, which is described in Chapter 5.

4.3.1 Systems Architecture Framework and System Definition

Research for this portion of my thesis was conducted via interviews with key stakeholders, complemented by a literature review. Literature included both academic literature as well as government and industry reports, blog posts, and newspaper articles. Analysis was structured according to the *Systems Architecture Framework* (SAF), as described by Rechtin and Maier (2010), which is described in more detail in Section 3.1.1. The SAF poses the following questions, which I used to structure my interviews and inquiries:

- *What is the system context?*
- *Who are the primary, secondary, and tertiary system stakeholders?*
- *What are the stakeholders' needs, desired outcomes and objectives?*
- *What functions does the system perform?*
- *What forms do those functions take?*
- *How do system functions and forms perform, operate, and change over time?*

To frame my SAF analysis and guide my choice of stakeholders and literature, I used the questions and tools developed by de Weck et al. (2011) to generate an initial specification of the sociotechnical system I would study. I considered several system definitions, including: "New England agriculture"; "the distributed sensor network that Responsive Environments had installed at Tidmarsh"; "the farming technologies that cranberry farmers use to modernize their farms"; "the MA DER restoration program"; and "regional residential development companies". Some of these system options seemed too broad, and some too narrow. For example, studying New England agriculture more broadly would have made it difficult to focus on the unique circumstances of the cranberry industry that have given rise to today's complex land use decision space. On the other hand, if I focused only on farm modernization technologies, I might miss the rich discourse around restoration and conservation.

Given my specific interest in land use decisions, agriculture, and climate change, I decided to define my system as *the agricultural, economic, restoration, and social activities related to cranberry* *farming, cranberry farmers, and cranberry farm land in Southeastern Massachusetts*. The system description is designed to capture activities that are closely related to and have an important impact on the cranberry industry itself, the people involved in the industry, and the land that, by virtue of the nature of agriculture, is at the center of these activities and livelihoods. This system definition was intended to be a high level, initial framing that would help focus my choice of literature and interview subjects during the contextual analysis phase. I expected that the exact boundaries of this system might evolve throughout the project, and that I would need to scope down my system of study (or select a subset of the system) as I proceeded into the modeling phase of my research.

4.3.2 Stakeholder Interviews

Between late 2020 and Spring 2022, I conducted nearly two dozen interviews with key stakeholders in the MA cranberry industry and bog restoration world, including cranberry farmers, field ecologists, restoration experts, non-profit employees, and government stakeholders. I was introduced to interviewees via connections stemming from my research group and the LO network. Glorianna Davenport, the founder of LO, connected me with an initial group of interviewees, and these interviewees were able to connect me to other relevant stakeholders. Information about the interviewees, the role of interviewees, and the timing of the interviews can be found in Table 4.1.

The interviews were 45-minute long, informal, semi-structured interviews conducted over Zoom or in-person. The interviews were not recorded. For the interviews conducted over Zoom, I took written notes on the content of the interviews. For the in-person interviews, I recorded audio notes on my phone directly following the interview. A list of interview questions was derived from the SAF structure and tailored to the context of the MA cranberry industry. For example, to address a SAF question such as *"What are the needs of primary stakeholders?"*, I asked questions such as *"What are the key goals of your work or your organization?"* and "*What are the key challenges you or your organization face?*" Interview questions were geared towards understanding the interviewee's role in the cranberry industry, gathering information on the current state of the cranberry industry in MA, and learning about specific situations and challenges that individuals or groups were facing. The full list of questions for the inter-

Stakeholder Name(s)	Date(s)	Stakeholder Role(s) and Organization	Interview Type
Brian Mayton	12/17/20	Living Observatory	Zoom
Glorianna Davenport	3/1/21, 4/9/22	Founder, Living Observatory	Zoom
Bob Wilber	3/8/21	Director of Land Conversation, Mass Audubon	Zoom
Chris Neill	3/9/21	Senior Scientist, Woodwell Climate	Zoom
Jessica Norris	3/9/21	Advisory Board Member, Living Observatory	Zoom
Alex Hackman	3/17/21, 8/9/21	Restoration Ecologist, MA Division of Ecological Restoration	Zoom
Christine Hatch	3/17/21	Associate Professor of Geosciences, UMass Extension	Zoom
Brian Wick	3/18/21, 9/9/21	Executive Director, Cape Cod Cranberry Grower's Association	Zoom
Kate Ballantine	3/18/21	Professor of Environmental Studies, Mt. Holyoke College	Zoom
David Boutt	3/19/21	Professor of Geosciences, UMass Amherst	Zoom
Linda Rinta	2/22/22	Cranberry farmer, West Wareham, MA	Phone call
Casey Kennedy	4/6/22	Research Hydrologist, USDA Agricultural Research Service	Zoom
Peter Stearns	4/23/22	Cranberry farmer	In-person
David Gould	4/23/22	Director, Department of Marine and Environmental Affairs, Plymouth, MA	In-person
Diane Peck, David Peck	4/23/22	Chair and member, Plymouth Open Space Committee	In-person
Zenas Crocker, Casey Chatelain	5/3/22	Executive Director and Deputy Director, Barnstable Clean Water Coalition	Zoom

Table 4.1: Stakeholder Interviews

views can be found in Appendix B. On an interview-by-interview basis, I selected initial interview questions from this list that were tailored to the background of the interviewee. These questions were used to initiate the interviews. Depending on the flow of the interview, some interviews diverted from the question list and I simply followed the direction of conversation.

After conducting each interview, I coded my notes from the interview based on the SAF. Qualitative coding involves labeling and organizing notes in order to structure observations into meaningful conclusions. My coding process involved labeling and organizing my notes to identify key themes and common ideas across interviewees. Drawing from the SAF, I labelled my interview notes with the following labels: Needs, Goals, Challenges, Partners/ Collaborators, Functions, and Forms. In particular, to develop the stakeholder mapping presented in Section 4.4.2, I used the Stakeholder Value Mapping method, drawn from Cameron et al. (2008), in which I first developed input–output models for each stakeholder, and then aggregated these individual models into a stakeholder network.

4.3.3 Literature Review

To complement the stakeholder interviews, I conducted a literature review that involved compiling and analyzing government and industry reports, historical accounts, and published academic research on cranberry farming and cranberry bog restoration. I used questions from the SAF, and the coding method and graphical templates described above to structure and drive my review of these materials.

My search for academic literature was conducted using Google Scholar, where I searched for publications containing the term *"cranberry farming Massachusetts"* and *"cranberry farming economics"*. Additionally, for industry and government reports, I searched the Massachusetts state website (`https://www.mass.gov/`), the United States Department of Agriculture (USDA) website (`https://www.usda.gov/`), and the National Agricultural Statistics Service website (`https://www.nass.usda.gov/`). For each of these sites, I used the site's built-in search functionality to search for items related to the terms *"cranberry farming "* and *"cranberry farming Massachusetts"*. Additionally, I drew publications from the LO website (`https://www.livingobservatory.org/publications`), the research portfolio of the USDA Agricultural Research Service, and the UMass Cranberry Station website (`https://ag.umass.edu/`

`cranberry/research-extension`). Reports and literature were selected based on their relevance to the research questions presented in this dissertation, specifically, the environmental, economic, and sociocultural impacts of cranberry farming and wetland restoration of cranberry bogs in MA. The full list of reviewed literature can be found in Appendix C. The main categories of literature reviewed were:

- *Government, industry, and historic reports* detailing the history of cranberry cultivation in MA, the economic impacts of cranberry production on the state, and the government programs directed towards cranberry growers and the cranberry industry.

- *Academic publications on cranberry farming*, including best management practices, and environmental impacts of cranberry farming. Many publications in this category came from, first, a branch of the USDA's Agricultural Research Service that focuses on the environmental impacts of cranberry farming, and second, the UMass Amherst Cranberry Station, which is an outreach and research center dedicated to maintaining and enhancing supporting the MA cranberry industry.

- *Academic publications on wetland restoration of cranberry farms*, including information on the MA DER restoration program, and the impacts of wetland restoration on water quality, GHG fluxes, and biodiversity, among other factors. Many of these publications came out of the LO research portfolio.

4.4 Results

Synthesizing the outputs of my coding analysis from stakeholder interviews with the information derived from my literature review, I implemented the SAF via a series of graphical "templates", developed by Wood (2021), to identify system context, conduct a stakeholder mapping, analyze stakeholder needs and objectives, and evaluate system functions and forms. It is important to note that this process was undertaken iteratively: during the course of my dissertation research, I frequently updated the results of my SAF analysis to reflect my new understanding of the system.

4.4.1 System Context

The first step of SAF involves identifying relevant contextual factors for the system. This contextual information is discussed in detail in Chapter 2. A visual summary of these factors is presented in Figure 4-1 to contextualize the rest of this results section.

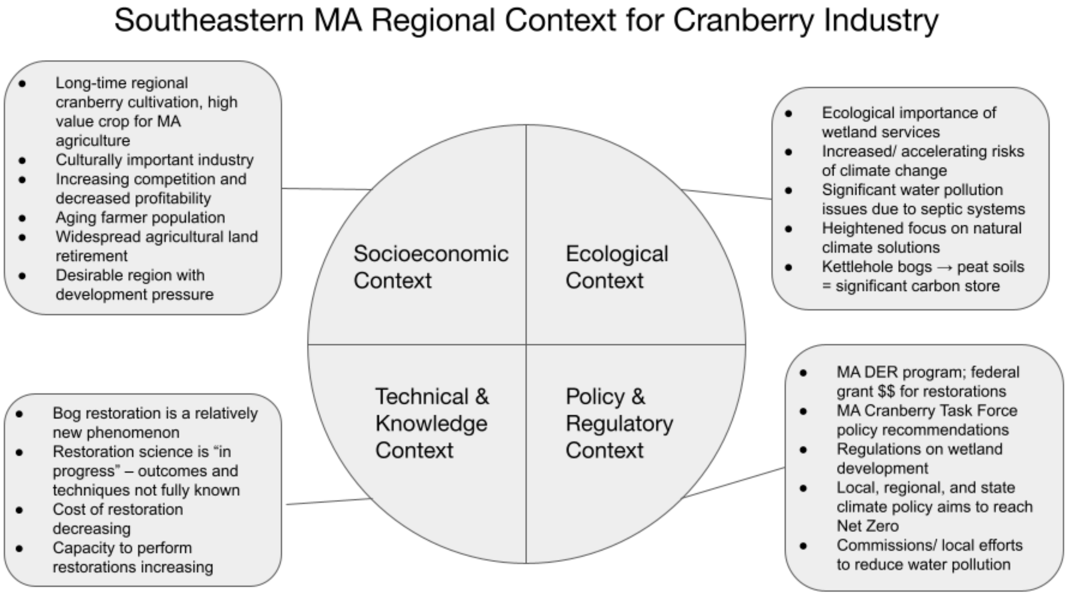


Figure 4-1: MA Cranberry Industry System Context

4.4.2 Stakeholders

A visual representation of my stakeholder mapping is shown in Figure 4-2. Primary stakeholders, who are the main entities making decisions within the system, are shown in blue. Secondary stakeholders, who can influence primary stakeholders through information, funding, or policies, are shown in yellow. Tertiary stakeholders, who might not have direct input on decisions, but who can benefit or be harmed by them, are shown in pink. The arrows between stakeholders show the actions through which stakeholders influence and impact each other. Via my literature review, stakeholder interviews, and SAF analysis, I identified the following four groups of primary stakeholders:

- Cranberry farmers

- MA Department of Ecological Restoration
- Local municipalities
- Local and regional nonprofits

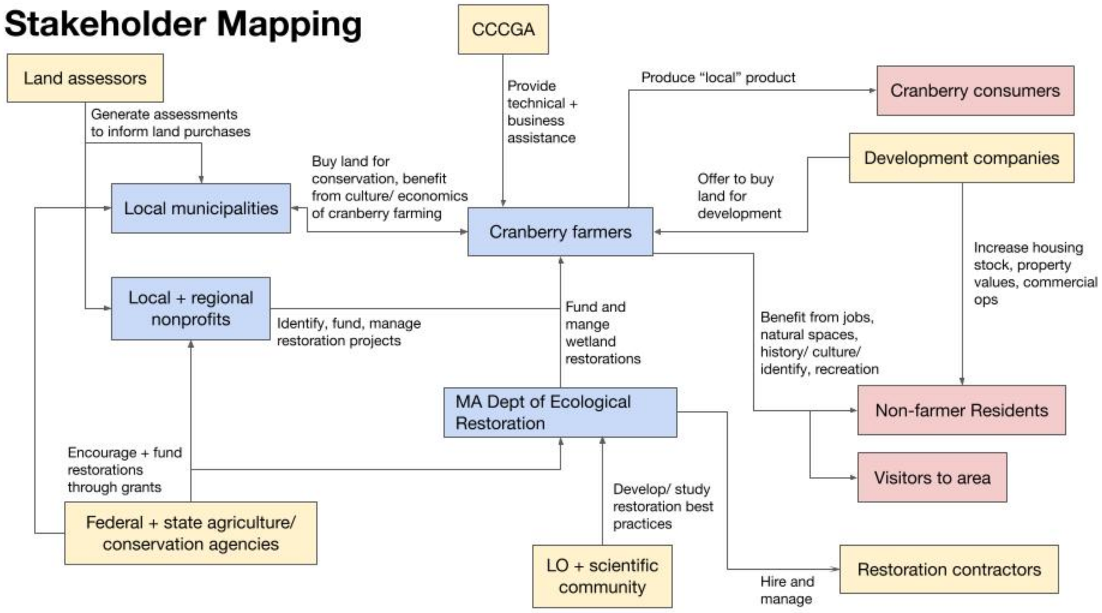


Figure 4-2: MA Cranberry Industry Stakeholder Mapping

Based on my interviews and subsequent analysis, I observed that each of these four primary stakeholders has land use decision-making power in the context of the MA cranberry industry: cranberry farmers, who tend to be the current land owners of cranberry bogs, have the option of selling their land to another entity, whereas the other three stakeholders tend to be organizations raising funds to buy land. Thus, these three stakeholder groups are making decisions about which parcels of land to purchase, how much to offer for the land, and what to use the newly purchased land for.

Surrounding the primary stakeholders are secondary stakeholders, who can influence primary stakeholders through information, funding, or policies. Based on my interviews and subsequent analysis, I observed that land assessors, a group of secondary stakeholders, play a critical role in the system. Land assessors produce land valuations that drive the dynamics of land purchasing and land use in the region. These land assessments directly impact how much money cranberry farmers are able to make by selling their land, and set a baseline for the pricing that developers, municipalities, or nonprofits are willing to offer to buy cranberry farms. However, because land assessments are traditionally based on the development value of cranberry farms, which is limited due to regulation in the Wetlands Protection Act, they are unlikely to capture the full potential value of cranberry farm land in terms of ecosystem services. Identifying the role of land assessors in the MA cranberry industry system emphasized the critical importance of land pricing and valuation in influencing land use decisions among stakeholders.

4.4.3 Needs and Objectives

Continuing with the next step of SAF, I present a summary of stakeholders' needs, desired outcomes, and system objectives in Table 4.2, which are derived from my coded notes from stakeholder interviews. In the context of the SAF, *Needs* are defined as a "stakeholder problem or gap in their desired state"; *Desired Outcomes* are defined as the "end state that the primary stakeholder desires to attain"; and *System Objectives* are defined as "high level description of what the program will do" (Wood, 2021).

My interviews and the stakeholder mapping process allowed me to identify competing and aligned needs and objectives within the system. One example of contrasting needs is that, in the absence of practical constraints, LO, the MA DER, and other restoration groups would like to see as many cranberry bogs as possible restored to their natural wetland state (A. Hackman, personal communication, August 9, 2021). In contrast, the CCCGA, which advocates and supports cranberry growers and the industry, would prefer to see cranberry bog renovations that would make the local industry more competitive (B. Wick, personal communication, March 18, 2021). Conversely, there are a number of stakeholders with aligned, if not entirely overlapping, needs and desired outcomes. For example, both local municipalities and certain non-profits have a need to provide and ensure clean water to local residents. Another shared "Desired Outcome" among the MA DER and certain non-profits is the preservation of open space; interestingly, the MA DER would like to preserve open space for environmental reasons, whereas some non-profits would like to preserve open space for recreation. Identifying these areas of alignment provided a critical underpinning for the system forms and functions analysis which is presented in the subsequent section.

4.4.4 Forms and Functions

The next step in SAF is to identify functions and forms of the system, where functions are actions or activities taken to achieve system objectives, and forms are the organizations, people, or programs that execute functions. In some cases, forms and functions already exist, while others are hypothetical forms and functions that could help achieve system objectives. Notably, some forms can be created by the primary stakeholders themselves, in order to accomplish their aims, while other forms can be built by secondary system stakeholders whose objectives might coincide with the primary stakeholders' or who wish to influence the primary stakeholders.

Here, I, as a secondary stakeholder – a researcher who was part of the LO and scientific community – wanted to support primary stakeholders in sustainable decision-making through information and tools. To achieve this desired outcome, I decided upon a particular system form: a web-based data exploration tool that visualized the results of an ecosystem services analysis. One objective of this particular system form was to identify the potential financial benefits of a cranberry bog restoration, and then to communicate those results in an accessible, user-friendly way. A system form that met this objective would support the needs and desired outcomes of cranberry farmers by reinforcing competitive sale pricing for cranberry bogs. For the other three primary stakeholders – the MA DER, local municipalities, and nonprofits – this system form could meet a system objective and support their needs by justifying investment in restoration projects, facilitating the acquisition of new funding sources, allowing them to offer more competitive pricing for cranberry farms, and helping them communicate the benefits of wetland restoration to their respective constituencies.

4.5 Discussion

The research in this portion of the dissertation aimed to answer two research questions concerning first, the structure and relationships of the MA cranberry industry, and second, identification of the environmental, economic, and social factors that are most important to industry and regional stakeholders. To address these questions, I used the SAF to structure a literature

Stakeholder Group	Stakeholder Need	Desired Outcomes	System Objectives
Cranberry farmers	Make a sustainable living, recoup investment in land, provide for family	Improve profitability of farming or sell land for sufficient price, possibly keep land natural/ open	Support/ justify competitive sale pricing for land
MA Dept of Ecological Restoration	Benefit people and the environment through restoration/ protection of watersheds and wetlands; improve knowledge of restoration best practices	Widespread restoration/ conservation of former cranberry farms; affordable and accessible restoration program	Support/ justify value of restoration projects; disseminate knowledge on restoration best practices; prototype novel funding models
Local municipalities	Provide clean drinking water, open/ recreational space to citizens, address climate threats	Be able to provide high standard of safe, climate-resilient living to all residents	Support investment in projects/ properties/ programs that support clean water, open space, climate resilience
Local and regional non-profits	Address risks of climate change and local environmental issues	Effective and affordable interventions to protect drinking water, become more climate resilient	Identify financing mechanisms, develop knowledge and best practices to support projects

Table 4.2: Needs and Objectives of Key Cranberry Industry Stakeholders

review and a series of stakeholder interviews to establish context for the project, identify system stakeholders and their needs, and understand how my work as a researcher could support these stakeholders' objectives.

One of the most important outcomes of the SAF analysis was the opportunity to dispel some of my assumptions about the MA cranberry industry and develop a deeper understanding of stakeholder needs. Coming into the project, I assumed that cranberry farmers were awash in offers from residential and commercial developers. I learned that, in fact, the real estate assessment process is exclusively based on development potential. Because wetland development is highly restricted under the Wetlands Protection Act, and many cranberry farm bogs are categorized as wetlands due to their historic ecology, most cranberry farms themselves cannot be developed. Thus, the development value of cranberry farm parcels is tied to the farm-adjacent uplands, and the amount of road frontage on the site, among other characteristics. For some farmers, these restrictions depressed offering prices, meaning development was not a lucrative or viable option.

Another important outcome of the SAF was identifying an area – bolstering land valuations for cranberry farms through ecosystem service valuation – where a single system form could satisfy the aligned, but not necessarily overlapping, needs of different stakeholders. The SAF results revealed how this proposed ecosystem service analysis could support competitive sale pricing for cranberry bogs, while justifying investment in restoration projects, enabling new funding streams, and generating language and information to better communicate the benefits of wetland restoration.

The SAF process crystallized for me the idea of approaching the land use decision challenge through the lens of financial incentives, and the opportunity there was in tying the value of land not to its development potential, but instead to the potential ecosystem services that could be realized on the land. Thus, the aim of the subsequent research in this dissertation is to estimate and communicate the potential value of ecosystem services in the region through the lens of three environmental factors, with the goal of changing how people think about land valuation, and supporting the needs and desired outcomes of primary stakeholders in the system.

4.5.1 Selection of Environmental Factors

Based on my interviews, literature review, and the outcomes of my SAF analysis, I selected the following three environmental factors to analyze further via ecosystem service modeling:

- *Regional water quality*: Excess amounts of nitrogen and phosphorus pose a major threat to clean drinking water and aquatic ecosystems in Southeastern MA. There are a variety of programs and technologies being deployed to address this issue, including restoring cranberry farms to wetlands, which could help filter and purify polluted water.

- *Habitat quality and biodiversity support*: Human activities, including farming and development, can threaten biodiversity through the application of chemical pesticides and the destruction of natural habitats. Given the development pressure in the area, there is interest in better understanding how wetland restorations could protect and support biodiversity.

- *Carbon storage and sequestration*: The world is experiencing rapid climate change due to GHG emissions. Though GHG emissions are a global problem, impacts are already being felt locally in MA. In this context, there is interest in wetland restorations for their potential to help draw down and sequester carbon, thereby reducing atmospheric GHG concentrations.

These environmental factors were selected because each was mentioned by a diversity of stakeholders as issues of relevant concern in the region. Additionally, each of these factors is being studied in connection with ongoing cranberry bog restorations. Thus, there is an interesting opportunity to evaluate the impact of wetland restorations through the lens of these factors. This analysis is the focus of Chapter 5 where it will be discussed in depth.

Chapter 5

Spatially-Explicit Analysis and Valuation of Key Ecosystem Services

5.1 Project Overview

The goal of this portion of the dissertation was to estimate the quantity, spatial distribution, and monetary value of three key ecosystem services under different restoration land use scenarios. This research utilized the Environment-Vulnerability-Decision-Technology (EVDT) framework to structure, design, and organize my analysis. InVEST ecosystem service models were used to model individual ecosystem services. The contributions of this work include spatially explicit maps of the estimated geographic distribution of ecosystem services under different land use scenarios, and maps of the estimated value these ecosystem services would represent over a 10-year period. Additionally, this research contributes economic analysis to contextualize the value of the ecosystem services in the region, and presents a method for prioritizing the wetland restoration of individual cranberry bogs. The data, maps, and analysis generated by this research form the basis of the geospatial data visualization tool presented in Chapter 6.

5.2 Research Questions

This portion of the thesis research was driven by the following research questions:

- R1: How do different restoration scenarios impact the quantity and distribution of key ecosystem services in the region?
- R2: What is the estimated value associated with ecosystem services under different restoration scenarios?
- R3: Which cranberry bogs should be prioritized for restoration?

5.3 Research Design and Methods

To address the above research questions, I structured my research inquiry as indicated in the system diagram in Figure 5-1. Drawing on the *Systems Architecture Framework* analysis described in Chapter 4, I selected three ecosystem services for further study. I then used the EVDT framework to organize and design my analysis. Using this framework provided structure for deciding which submodels to use, which data to incorporate, and how to integrate the results of these different submodels. After designing my analysis plan using EVDT, I used InVEST to model the three ecosystem services under different land use scenarios. When possible given the InVEST model outputs, I conducted economic valuation of ecosystem services and used regional socioeconomic data to contextualize the results and integrate them into a prioritization index. The results of the InVEST modeling and this economic analysis – which are largely in a geospatial format – are visualized and presented in a user-friendly webtool, as described in Chapter 6.

5.3.1 Using EVDT to Structure Analysis

The EVDT framework is introduced in detail in Section 3.1.2. In Figure 5-2, I present the EVDT diagram used to structure my environmental and economic analysis of the MA cranberry industry. The framework consists of uniting various submodels that each answer a different question, and identifying relevant supporting data to calibrate and run those submodels.

The Environment submodel asks, "*What is happening in the natural environment?*" In my EVDT framework, the state of the natural environment was determined using satellite data products including land-use-land-cover (LULC), topography, and precipitation maps, among

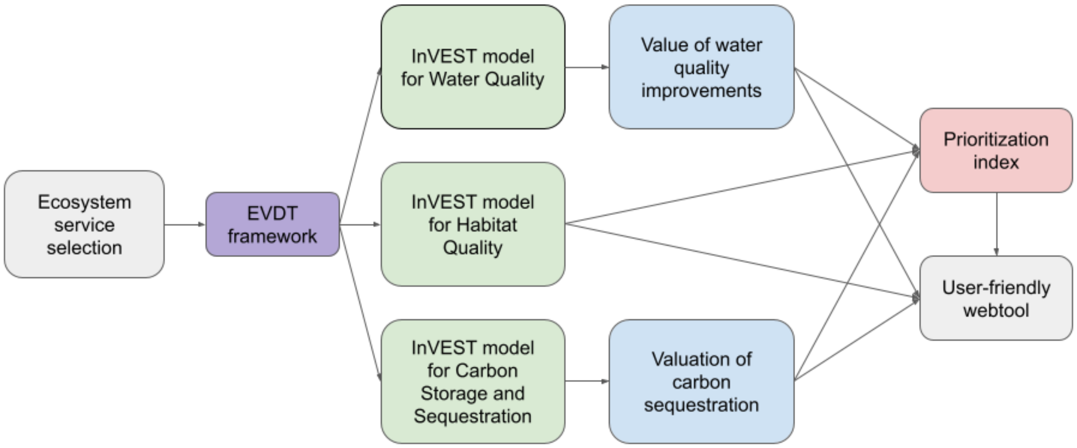


Figure 5-1: System Diagram of Research Approach in Chapter 5

others. I used these data combined with information about the location of current cranberry farms to generate different land use scenarios, where each hypothetical land use scenario represented a different potential mix of restoration and farming on today's current cranberry farms.

The Vulnerability submodel asks, *"How will humans be impacted by what is happening in the natural environment?"* This submodel contains the core analysis of this case study. Here, I used several InVEST models to estimate the geospatial distribution of ecosystem services across the landscape, given the different land use scenarios coming out of the Environment submodel. Additionally, I combined economic heuristics and socioeconomic data on population and town budgets to contextualize the economic impacts and benefits of ecosystem services generated by wetland restorations.

The Decision submodel asks, *"What decisions are humans making in response to environmental factors and why?"* In some EVDT implementations, this submodel uses agent-based modeling and discrete event simulation to simulate human behavior and policy consequences. In this case, I do not attempt to model human decisions; instead, this submodel represents the data visualization and exploration tools I develop using the results of the Vulnerability submodel, which serve to support actual human decision-making instead of model it. In my EVDT im-

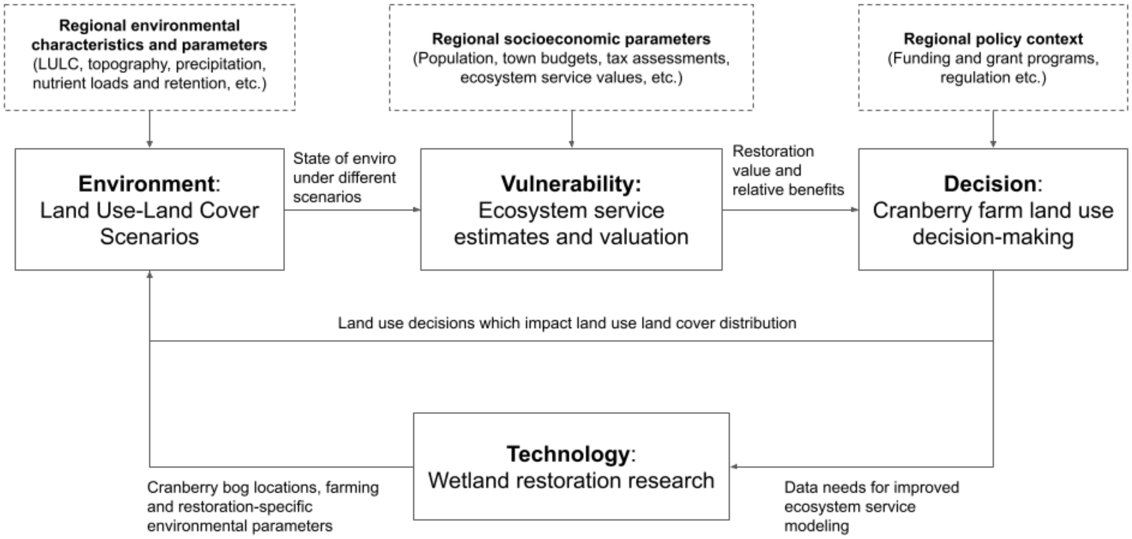


Figure 5-2: EVDT Diagram

plementation the Decision submodel simply reflects the real human land owners who will be making decisions about their land. These decisions then feed back into the state of the Environment, and also inform the goals and agenda of the Technology submodel.

Finally, the Technology Model asks, *"What technology system can be designed or acquired to provide high quality information that supports human decision making?"* In EVDT implementations that focus on technology design, this submodel might be a more traditional engineering model that captures stakeholder values to drive system design. Here, I use the Technology submodel to broadly reference the wetland restoration research programs that are being conducted by LO, local universities and research institutions, and the USDA Agricultural Research Service. These research programs, in turn, help develop farming and restoration-specific environmental parameters that inform the Environment model.

The EVDT framework allows one to structure and design a systems-level analysis of a particular case study. While my work did not address every element represented in Figure 5-2, the framework allowed me to focus on my core areas of analysis while keeping in mind the system dynamics and analysis needs of the MA cranberry industry more broadly.

5.3.2 Preparation of Land Use Scenarios

In R1, I ask: *"How do different restoration scenarios impact the quantity and distribution of key ecosystem services in the region?"* A key preparatory step for addressing this research question was to develop different scenarios representing different uses of land. Land-use land-cover (LULC) data layers are essentially maps where every pixel of the map has a value that corresponds to the use of land at that point, whether it's a farm, a wetland, a forest, or a city. Use of different LULC scenarios, which generate different configurations and distributions of land use, are a common method for performing regional environmental analyses (Hamel & Guswa, 2015).

Creating static LULC scenarios was necessary given the constraints of the InVEST ecosystem service models, as InVEST models cannot be run "on the fly". Thus, inputs such as LULC maps had to be determined in advance. In this case, I wanted to assess the impacts of potential cranberry bog restorations on the selected ecosystem services, so I needed to generate LULC layers that represented different combinations of farming and wetland restoration. Because I wanted to isolate the impacts of restoration, I did not generate scenarios that represented other potential land use, I focused solely on cranberry bogs that could potentially switch land use type to restored wetland.

Using QGIS, an open-source geospatial information system application, I created 11 different land use layers, each with different distributions of farming and restoration. To do so, I modified a data layer that contained all current cranberry bogs, which was accessed through the MA DER. The layer contained the outlines of all current cranberry farms, *not* the surrounding properties or uplands. The first LULC scenario layer corresponded to the state of the industry today, which meant that all today's current cranberry farms were labelled as farms, not restored wetlands. This was the "100% farming and 0% restoration" case. For the next scenario, I randomly selected 10% of the bogs to be designated as restored wetlands, while leaving the remaining 90% of bogs as farms. Then I randomly selected another random 10% of bogs so that the distribution was 80% farming and 20% restoration, and so on, up to 100% restoration case, where all today's current cranberry farms were labelled as restored wetlands. Visualizations of the 100% farming, 50% farming, and 100% restoration cases are shown in Figures 5-3, 5-4, and 5-5, with cranberry farming visually represented in red, and restored wetlands in green. Note that these images only show the farming and restoration assignments of cranberry bogs, not

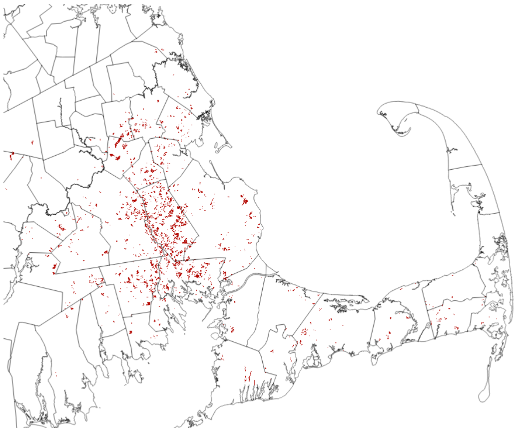


Figure 5-3: 100% Farming, 0% Restoration cranberry bog assignments

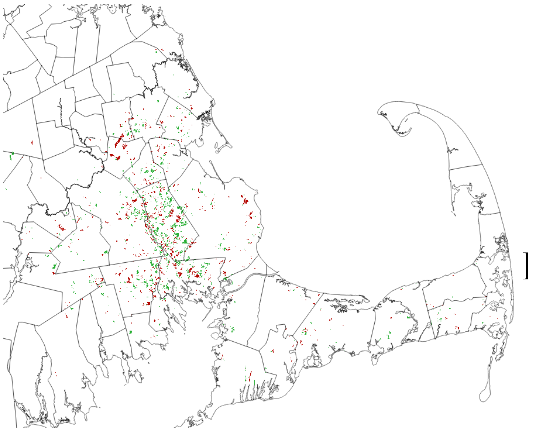


Figure 5-4: 50% Farming, 50% Restoration cranberry bog assignments

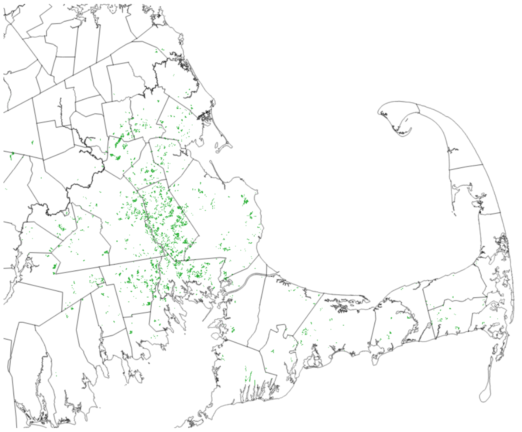


Figure 5-5: 0% Farming, 100% Restoration cranberry bog assignments

the surrounding land use.

This process created maps where each cranberry farm pixel was labelled as either farming or restoration, leaving the rest of the map blank. To create complete LULC files where every pixel had a value, I used QGIS to merge the randomly assigned farms or wetlands with the National Land Cover Database's 2019 map (USGS, 2019). The LULC map, with a detailed pop-out showing the generated restoration scenario, can be found in Figure 5-6. These LULC layers were then used as a key input in each of the InVEST ecosystem service models.

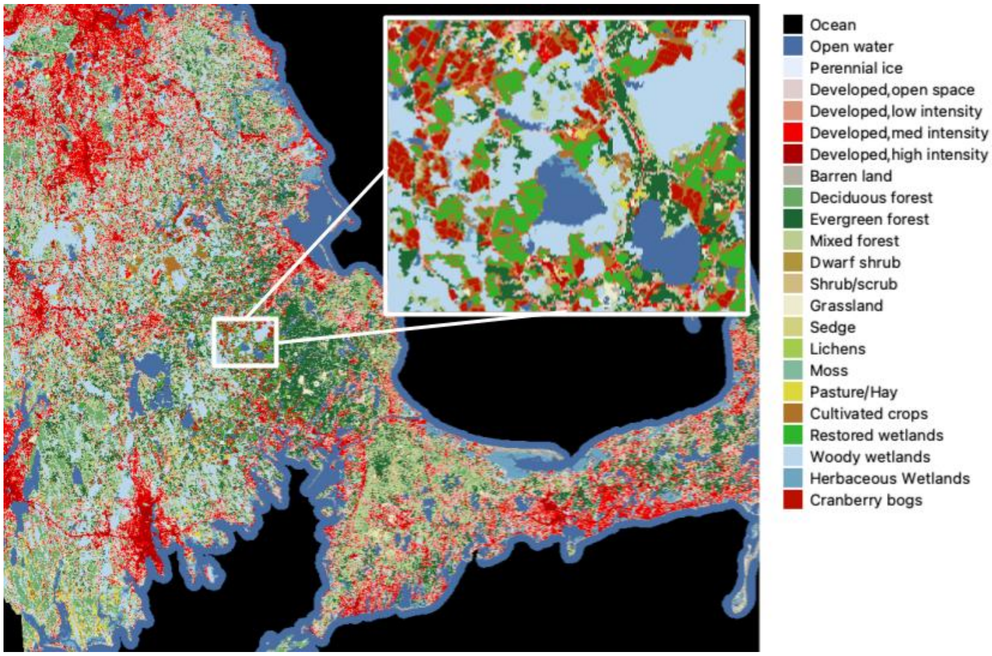


Figure 5-6: LULC Map showing detail of 50% farming and 50% restoration scenario

5.3.3 Ecosystem Service Models

Under each of the 11 different land use scenarios, I wanted to model three different ecosystem services, to understand how the quantity and distribution of these services would change based on different uses of land. The three ecosystem services chosen for modeling are listed here. Further discussion of the selection of these ecosystem services can be found in Section 4.5.1.

- *Water purification*: specifically, the amount of nitrogen and phosphorus that a given area of restored wetland could prevent from reaching streams and bodies of water
- *Habitat quality*: the ability of a specific area of restored wetland to support healthy biodiversity
- *Carbon storage and sequestration*: the ability of a certain area of restored wetland to store increasing amounts of carbon over time

To model these ecosystems services, I selected corresponding ecosystem service models from the suite of InVEST modeling tools. Selection of InVEST as an overall ecosystem service modeling tool is discussed in detail in Section 3.2.1. The InVEST models I used were:

- *Nutrient Delivery Ratio (NDR) model*: quantifies the ability of the landscape to retain nitrogen and phosphorus and keep these harmful nutrients out of streams and bodies of water

- *Habitat Quality (HQ) model*: estimates habitat quality, or the ability of a habitat to support biodiversity, on a relative scale of 0-1

- *Carbon storage and sequestration model*: estimates carbon storage based on land use, and changes in carbon storage (e.g. carbon sequestration) over time

In general, the data inputs to these models are geospatial data, either raster or vector files. Raster files are rectangular grids of data representing a geographical area, where each pixel has a different value that represents a geospatial quantity, such as elevation or land use type. Vector files are a different type of geospatial data made up of polygons, lines, or points of interest. The InVEST models utilize both raster and vector data, and produce spatially explicit outputs showing the distribution of ecosystem services across landscapes.

5.3.4 Preparing and Calibrating the Nutrient Delivery Ratio Model

I used the InVEST Nutrient Delivery Ratio (NDR) model to estimate the ecosystem service of water purification under different LULC scenarios. Excess amounts of nitrogen and phosphorus, also called nutrients, are damaging to aquatic ecosystems. For every pixel in a landscape map, the NDR model specifically calculates the amount of nutrient leaving each pixel, and the ratio of that nutrient that makes it to the stream in the watershed. In other words, this model quantifies the ability of a landscape to retain harmful nutrients and keep them out of bodies of water. In certain landscapes, such as paved urban areas, most nutrients will run off into the watershed. Other land uses, such as wetlands, are able to retain those nutrients in vegetation, or by converting them into less harmful forms through biochemical processes.

In the model, the amount of nutrient, or "nutrient load", coming from each pixel is a function of land use type, and given in user-defined table. Each land use type has a different nutrient load associated with it that is an average for that type of land cover based on factors like fertilizer use or residential density. The user must also input to the model the ability of each land use type to absorb and retain nutrient, which is also given in the user-defined table. For each pixel a *delivery ratio* is calculated from the slope and area of upslope areas relative to that pixel, the slope and length of the downslope path, and the ability of pixels on that path to retain nutrient. The ratio estimates the fraction of nutrient, from each pixel, that makes it to the stream, as visualized in Figure 5-7.

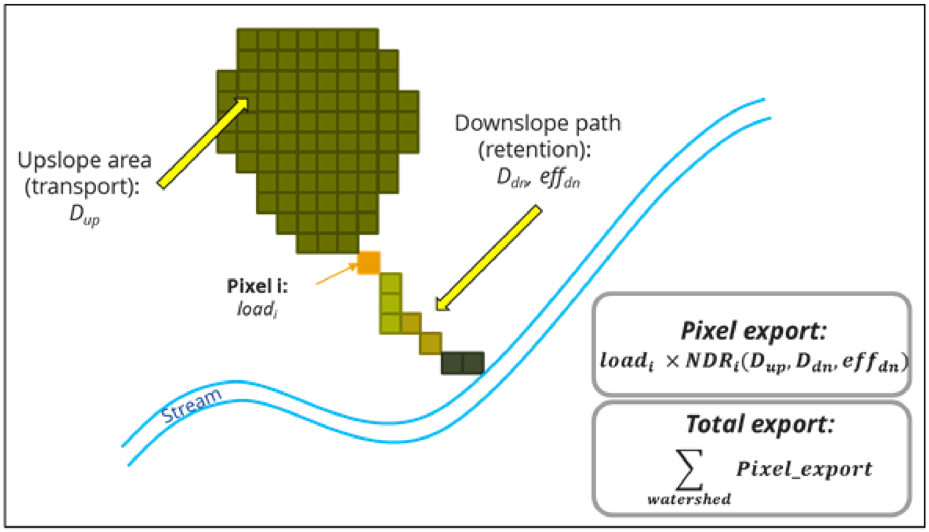


Figure 5-7: NDR Model Diagram Source: InVEST User Guide

Data Collection and Preparation

The inputs to the NDR model are as follows:

- Digital elevation model
- LULC map
- Precipitation map
- Watersheds map
- Biophysical table with information on nutrient loading rates and nutrient retention by LULC type
- Input parameters: Borselli K Parameter, Threshold Flow Accumulation, and Critical Length

Most of these data were collected from publicly available sources. The process for generating LULC maps is described in Section 5.3.2. The biophysical table was developed through a literature search process, which is described in more detail below. The calibration process for the input parameters is also described in more detail below. Information on data sources can be found in Appendix D.

Creation of Biophysical Table

The *biophysical table* contains information on nutrient loading rates and nutrient retention by LULC type. It is a key input to the NDR model, and requires conducting a literature search to discover region-specific values for different land use types. Developing the biophysical table was one of the most time-consuming parts of working with the NDR InVEST model.

For each LULC type, the biophysical table requires a *load_n* and a *load_p* value, which stand for *nitrogen load* and *phosphorus load*. These values are given in $\frac{kg}{ha*year}$, and represent the nutrient loading for this land use class: essentially, the average amount of nitrogen or phosphorus that would be expected to come from a given area of a particular LULC type. Nitrogen and phosphorus are generated through certain biogeochemical processes, or can come from synthetic sources such as fertilizers or pesticides.

For each LULC type, the biophysical table also requires *eff_n* and *eff_p* values, which indicate the "nutrient retention efficiency" of that particular land type, given as a unitless value between 0 and 1. As described in the InVEST user guide, this value is "the maximum proportion of the nutrient that is retained on this LULC class" (Sharp et al., 2020). In general, natural vegetation land use types, such as forests or wetlands, have have retention efficiency, while developed land use types, such as industrial or high-density residential areas, have low retention efficiency.

To assemble a biophysical table for the MA cranberry region case study, I used the biophysical table from Han et al. (2021) as a starting point, because their biophysical table contained values for a watershed in the same climate zone as Southeastern MA. I further refined my table values using values from White et al. (2015), Hobbie et al. (2017), and the InVEST nutrient database (Sharp et al., 2020).

For values specific to the cranberry farm land use type, I drew on research from the USDA Agricultural Research Service, which conducts focused research on nutrient cycling in cranberry farms in Southeastern MA (Kennedy, 2019; Kennedy et al., 2020). For cranberry farms that had been restored to wetlands, I used the same loading and retention efficiency values as the emergent herbaceous wetlands land use type.

The full biophysical table and further explanation of parameter choices can be found in Appendix D.

Sensitivity Analysis

Sensitivity analysis was performed to analyze how the uncertainty from model parameters compared to uncertainty in environmental inputs, using the following method adapted from Hamel and Guswa (2015). The three parameters calibrated were:

- The Borselli K parameter (Kb), which is a hydrologic calibration parameter that "determines the shape of the relationship between hydrologic connectivity and the nutrient delivery ratio" (Sharp et al., 2020).
- The Threshold Flow Accumulation (TFA), which is a "a stream delineation algorithm parameter that specifies the number of upstream pixels that must flow into a pixel before it is classified as a stream" (Sharp et al., 2020).
- Critical length (CL), which is the distance after which a certain LULC retains nitrogen or phosphorus at its maximum efficiency

A standard range and default value were identified for each parameter from the literature and the InVEST user guide (Hamel & Guswa, 2015; Sharp et al., 2020). These ranges and values are given in Table 5.1.

Parameter	Standard Range	Default Value
Kb	0.5 - 3.5	2.0
TFA	50 - 2000	1000
CL	30 - 300	150

Table 5.1: Standard range and default values for NDR calibration parameters

While two of the three parameters were held constant, the third parameter was varied over the selected range, and the NDR model was run for each value in the range of the varying parameter. The model was run on a calibration subset of 10 of the region's subwatersheds using the InVEST Python package.

To evaluate the sensitivity of the model to changes in these calibration parameters, I analyzed the change in the amount of nutrient export at the subwatershed level for different values of each calibration parameter. The percentage difference in results was averaged across the 10 subwatersheds, and was calculated relative to the percentage change in the model parameter from its default value. Results are summarized in Table 5.2, and visualized in Figures 5-8, 5-9, and 5-10.

Parameter	Change in Parameter (%)	Average Change in N export (%)	Average Change in P export (%)
Kb	50% decrease	20% decrease	19% decrease
Kb	50% increase	8% increase	8% increase
TFA	40% decrease	8% increase	4% increase
TFA	40% increase	7% decrease	4% decrease
CL	40% decrease	3% decrease	4% decrease
CL	40% increase	3% increase	4% increase

Table 5.2: Results of NDR model parameter sensitivity analysis

These tabular results, along with the visualizations in Figures 5-8, 5-9, and 5-10, suggest that model outputs are quite sensitive to selection of Kb, particularly for lower values of Kb. Model outputs are also sensitive to TFA, particularly for lower values. The sensitivity distributions for CL are much smaller and more symmetric, suggesting that model outputs are not particularly sensitive to the choice of CL.

Model Calibration

The goal of model calibration was to select the combination of model input parameters that produced model outputs that most closely matched observed outputs. This method was adapted from Hamel and Guswa (2015). To carry out the calibration, I ran the NDR model for every combination of model input parameters given in the standard ranges identified during the Sensitivity Analysis. With 7 options for Kb, 11 options for TFA, and 10 options for CL, there were 770 model calibration runs overall. As in the Sensitivity Analysis, the model was run on a calibration subset of 10 of the region's subwatersheds are using the InVEST Python package.

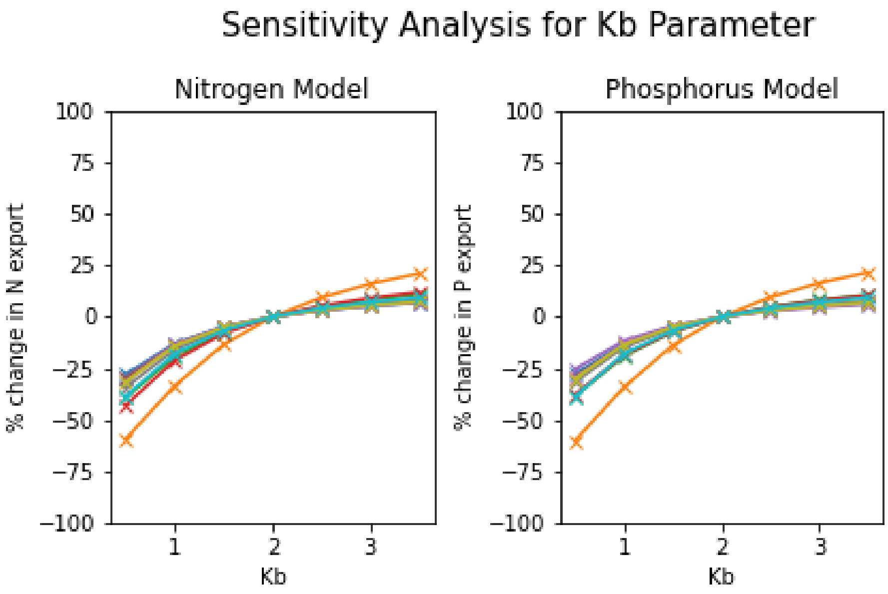


Figure 5-8: KB Sensitivity

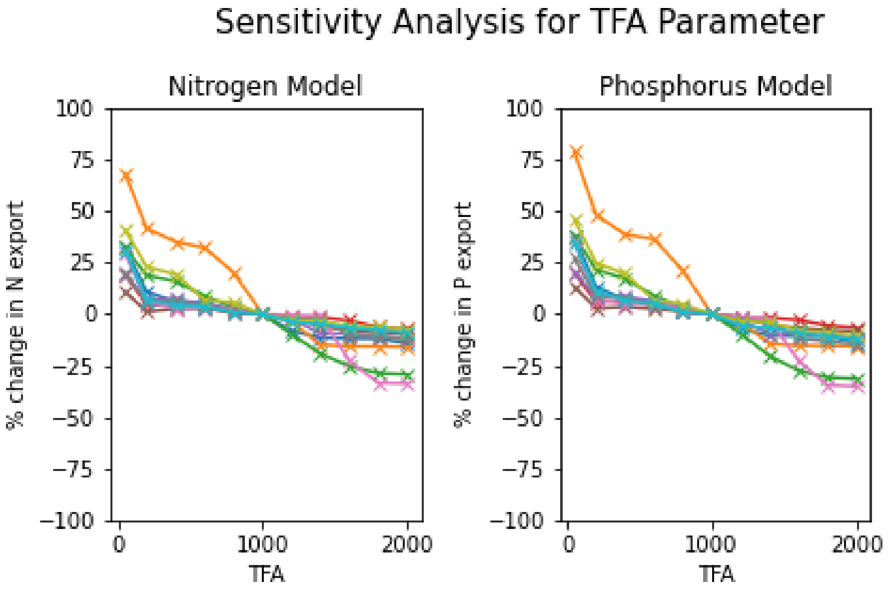


Figure 5-9: Threshold Flow Accumulation (TFA) Sensitivity

The model outputs used for calibration were the estimated total nitrogen and total phosphorus export for each subwatershed. These modelled values were compared to observed data from the 2012 USGS SPARROW model, a national-scale model that uses USGS monitoring data combined with watershed characteristics to model watershed contaminants (Ator, 2019). The percent difference between observed and modelled export was calculated for each of the

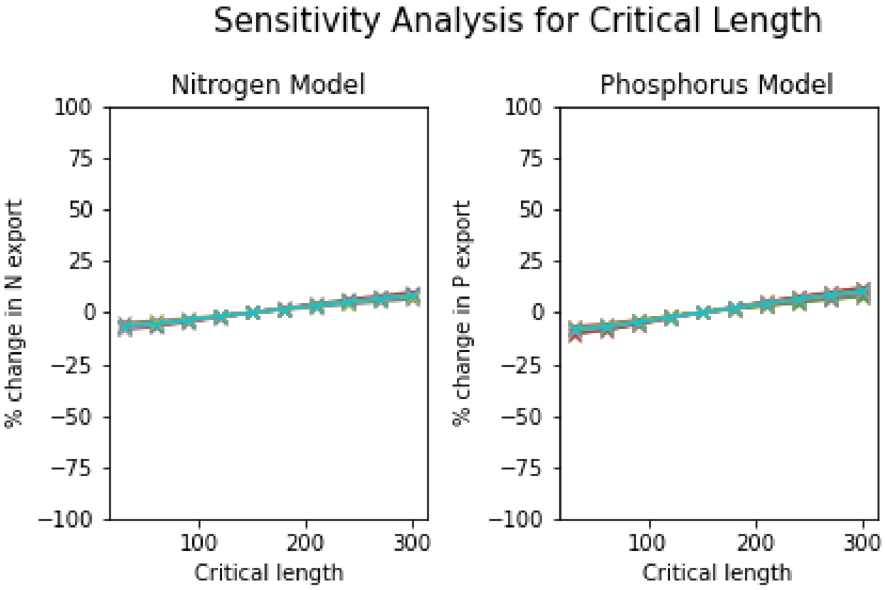


Figure 5-10: Critical Length (CL) Sensitivity

10 subwatersheds, and then averaged across the subwatersheds for each of the 770 calibration runs.

I selected the combination of input parameters across all calibration runs that minimized the average percent difference between observed and modelled data across all subwatersheds. Different settings were selected for the nitrogen and phosphorus submodels. The selected calibration values can be found in Table 5.3.

Nutrient Model	Kb Value	TFA Value	CL Value
Nitrogen	3.5	50	300
Phosphorus	3.5	2000	270

Table 5.3: Selected values after NDR model parameter calibration

Figures 5-11 and 5-12 compare the modelled output using the selected parameters with the observed USGS SPARROW data for both nitrogen and phosphorus export. The modelled and observed data are shown for the 10 calibration subwatersheds. All four figures are shown with the identity line that would indicate a perfect match between modelled and observed data.

Within each set of figures, the figure on the left shows how well InVEST *ranks* subwatersheds in terms of nutrient export, relative to the observed SPARROW data. This graph indicates whether the subwatershed with the highest observed nutrient export is also the sub-

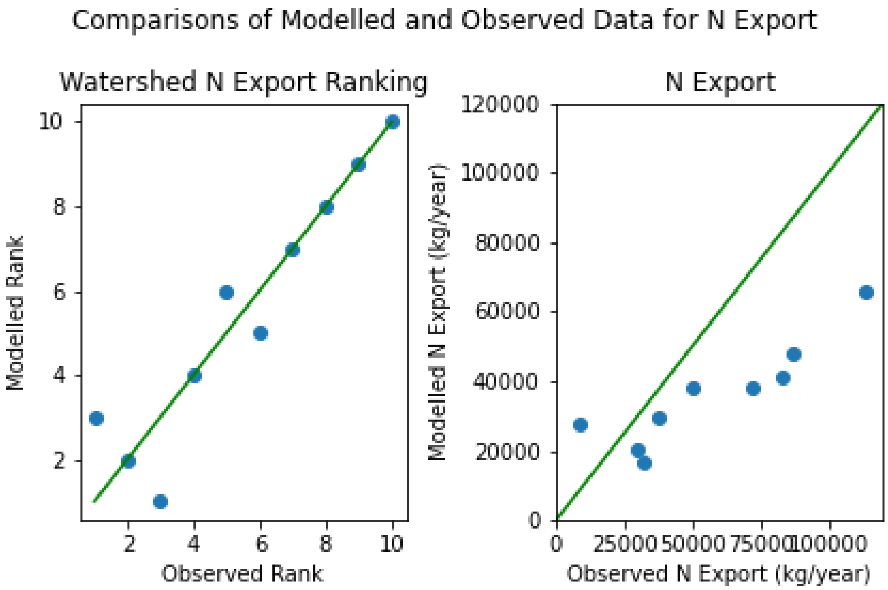


Figure 5-11: NDR Nitrogen Model Performance

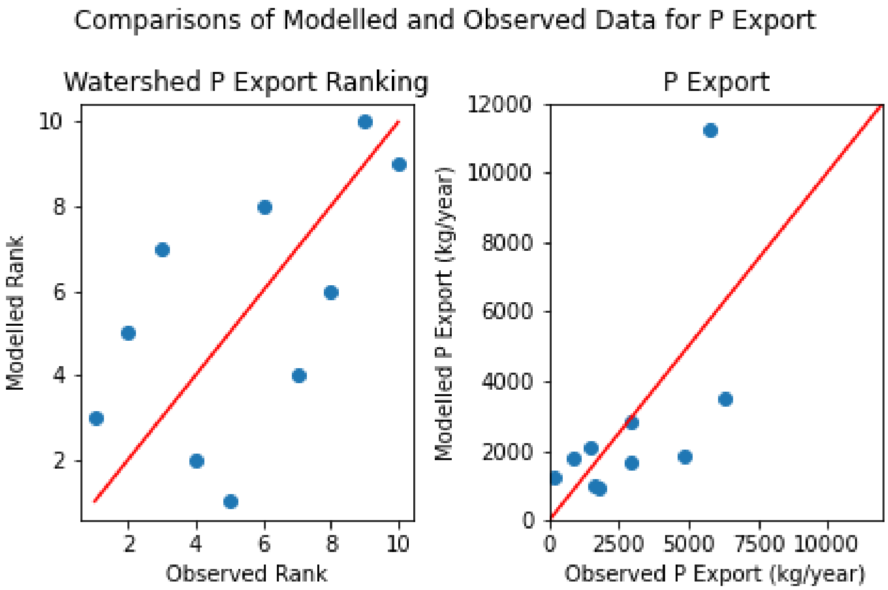


Figure 5-12: NDR Phosphorus Model Performance

watershed with the highest modelled nutrient export. In terms of ranking, the model performs better in the nitrogen case than in the phosphorus case; however, the absolute amounts of observed phosphorus export are fairly similar to each other, which means it's easier for the model to swap the rankings of subwatersheds. Within each set of figures, the figure on the right shows how well InVEST estimates actual nutrient export relative to the observed SPARROW data, for each subwatershed. The figures show that InVEST tends to somewhat underestimate both nitrogen and phosphorus export.

Based on this analysis, I concluded that InVEST represented the relative amounts of subwatershed-level nutrient export well enough to facilitate useful spatial comparisons. I proceeded to use the selected calibration settings to run the NDR model on different land use scenarios.

5.3.5 Preparing and Calibrating the Habitat Quality Model

I used the InVEST Habitat Quality model to estimate the ecosystem service of habitat provision under different LULC scenarios. For every pixel in a landscape map, the Habitat Quality model computes a relative habitat quality score that ranges from 0 to 1 based on land use type and proximity to man-made threats, including roads, agriculture, and development. The habitat quality score is not related to any specific biodiversity metric, but indicates an area's general ability to support healthy biodiversity. Input data include maps of different threats to biodiversity, along with user-supplied weighting factors to indicate how sensitive different environments are to different threats. For this study, the threats I modelled were agriculture, development, and roads.

Data Collection and Preparation

The inputs to the Habitat Quality model are as follows:

- LULC map
- Threat maps showing the extent and location of the selected threats in the region
- Threats table with information on the distance over which threats in the region can impact or harm biodiverse habitats
- Sensitivity table which indicates whether each LULC class can be considered a habitat for biodiversity, and for each threat-LULC type pair, how sensitive that LULC type is to that threat

The process for generating LULC maps is described in Section 5.3.2. The threats and sensitivity tables were developed by adopting standard parameter values given in the InVEST user guide, and then calibrating these parameters to the Southeastern MA region (Sharp et al., 2020). This calibration process is described in more detail below. Further information on data sources and the full threat and sensitivity tables can be found in Appendix D.

Sensitivity Analysis

As with the NDR model, sensitivity analysis was performed with the Habitat Quality model to analyze how the uncertainty from model parameters compared to uncertainty in environmental inputs, using the method adapted from Hamel and Guswa (2015). Here, the parameters varied were the sensitivity to threats, the threat weight, and the threat distance, across all land use types and threat types. Relative to a starting value, each input was reduced by 25% and then increased by 25%. While two of the three parameters were held constant at their starting value, the third parameter was varied over the selected range, and the Habitat Quality model was run for each value in the range of the varying parameter. The model was run on the LULC map of Southeastern MA using the InVEST Python package. The percentage difference in average habitat quality across the entire landscape was calculated relative to the percentage change in the model parameter. Results are presented in Table 5.4 and visualized in Figure 5-13.

Parameter	Change in Parameter (%)	Change in Habitat Quality Average (%)
Sensitivity to threats	25% decrease	2.49% increase
Sensitivity to threats	25% increase	2.35% decrease
Threat weight	25% decrease	No change (0.0% change)
Threat weight	25% increase	0.63% increase
Threat distance	25% decrease	0.3% decrease
Threat distance	25% increase	0.39% increase

Table 5.4: Results of Habitat Quality model parameter sensitivity analysis

These results suggest that model outputs are somewhat sensitive to the "Sensitivity to threats" parameter, and not very sensitive to the threat weight and threat distance parameters. However, these results may also be an artifact of the distribution of threats in the region and the way the model operates; because the threat maps and habitats that are adjacent to these threats make up a relatively small portion of the overall area of the region, changes in threat value and distance may not have a significant overall impact on average habitat quality. This line of reasoning suggests that further or alternative analysis could improve characterization of the sensitivity of the model; however, as this was not the primary focus of this research, I did not opt to run a second round of sensitivity analyses.

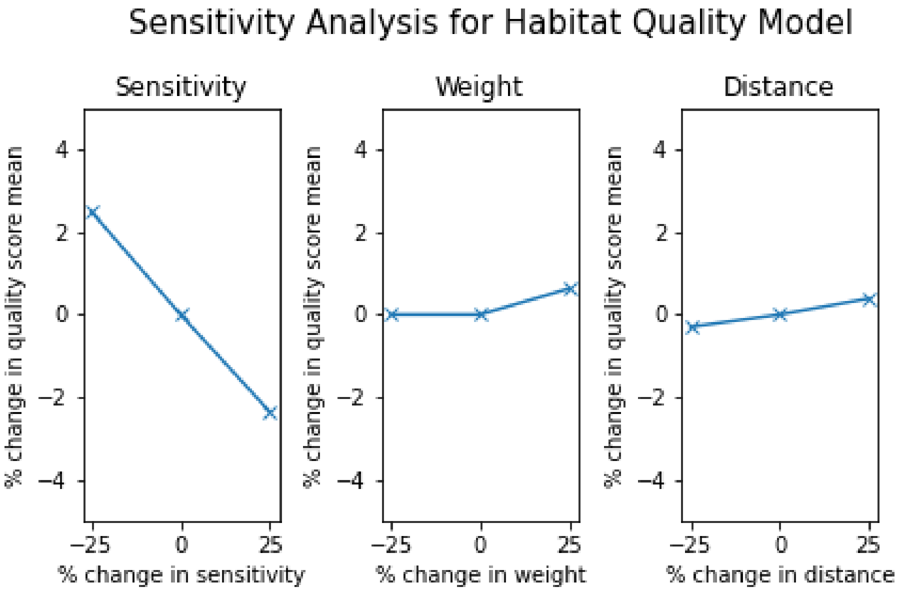


Figure 5-13: HQ Model Sensitivity

Model Calibration

As in the case of the NDR model, the goal of model calibration was to select the combination of model input parameters that produced model outputs that most closely matched observed outputs. This method was adapted from Hamel and Guswa (2015). While the NDR model produces a concrete output value that can easily be compared to observed data, the Habitat Quality model produces a habitat quality index that is not used in other research settings. To overcome to this constraint, for the "observed" data for calibration, I decided to use the *Core Habitats* layer from BioMap2, which is a mapping project developed by the Massachusetts Natural Heritage and Endangered Species Program and The Nature Conservancy and identifies key natural habitats in the state (Woolsey et al., 2010). A portion of the BioMap2 *Core Habitats* layer is shown in Figure 5-14. To better compare BioMap2 with the model outputs, I removed BioMap2 features with areas smaller than 1 acre or that had no overlap with the region of study. I then assigned a value of 1, corresponding to a high habitat quality, to all points in the *Core*

Habitats layer polygons, which are shown in green in Figure 5-14. The value of points outside these polygons was set to 0.

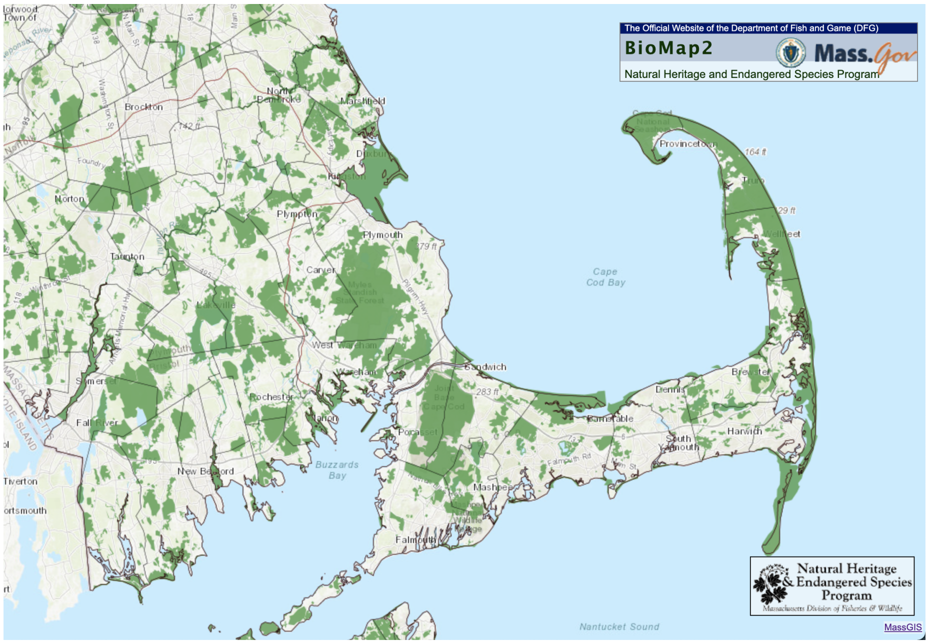


Figure 5-14: BioMap2 *Core Habitats* layer (Woolsey et al., 2010)

To carry out the calibration, I ran the Habitat Quality model for every combination of model input parameters given in the ranges identified during the Sensitivity Analysis. With 3 options for "sensitivity to threats", 3 options for "threat weight", and 3 options for "threat distance", there were 9 model calibration runs overall. As in the Sensitivity Analysis, the model was run on the LULC map of Southeastern MA using the InVEST Python package.

For each model calibration run, the average habitat quality within each of the BioMap2 regions was calculated using Zonal Statistics in QGIS. The model calibration that produced the highest average scores within all BioMap2 regions was selected; these model parameters were: sensitivity to threats 25% lower than the original value, threat distances 25% higher than the original value, and threat weights 25% higher than the original value. It is important to note that this calibration method allowed me to select the calibration parameters that do a good job of identifying areas of high habitat quality. However, this method did not tune the parameters to do a good job identifying areas of low habitat quality (i.e., regions outside the BioMap2 Core Habitats regions).

5.3.6 Preparing the Carbon Sequestration Model

I used the InVEST Carbon Storage and Sequestration model to estimate the ecosystem service of carbon sequestration under different LULC scenarios. For every pixel in a landscape map, the Carbon Storage and Sequestration model estimates carbon storage at that point based on the average carbon pools of different land use types. Carbon sequestration is modelled as the difference between carbon storage at different points in time, for each pixel in the landscape. Carbon pools information is supplied in a user-defined table, which was derived from a variety of sources, and in particular, based on recent research on the carbon sequestration potential of restored wetlands by Hemes et al. (2019).

It is important to discuss here some of the nuance around GHG emissions, wetlands, and carbon modeling. The InVEST Carbon Storage and Sequestion model is a heavily simplified model that uses carbon accounting based solely on the average carbon pools in different land use types. This model does not take into account the complicated biogeochemical processes of the carbon cycle, or other important physical attributes like soil type and hydrology. Additionally, it is important to note that the GHG balance of wetlands is complicated by methane emissions. Wetlands tend to sequester carbon, but they are also known to emit methane, which is a different powerful greenhouse gas. When methane emissions exceed carbon sequestration, wetlands can be a source of emissions, contributing to the atmospheric concentrations of GHGs causing climate change. When carbon sequestration exceeds methane emissions, wetlands can help remove GHGs from the atmosphere, lessening the threat of climate change. There is uncertainty and ongoing scientific discourse around the exact balance of carbon and methane fluxes in wetlands, both in native wetlands, and in restored wetlands, as in this case.

However, there is some research to suggest that restored peat wetlands, such as the restored cranberry farms in Southeastern MA, become net sinks for GHGs over the long term. A recent paper by Hemes et al. (2019) found that restored peat wetlands in California begin to sequester carbon shortly after restoration, become net climate benefits relative to farming, even with methane emissions, over decade scale, and likely become net sinks for GHGs over century scale. Ultimately, keeping this nuance in mind, I believe it is important to consider carbon storage and sequestration alongside other ecosystem services, especially in light of an active and growing carbon payments space, which could potentially link these restorations to a novel source of funding.

Data Collection and Preparation

The inputs to the Carbon Storage and Sequestration model are as follows:

- Present and future LULC maps
- Carbon pools table with information on average carbon storage for each LULC class

The process for generating LULC maps is described in Section 5.3.2. In the context of this model, I used the 100% farming LULC map to indicate present-day LULC conditions, and I used the 10 other LULC with different distributions of cranberry farming and restoration to represent 10 potential LULC future conditions.

Carbon data for the carbon pools table was drawn from a literature search, including a National Greenhouse Gas Inventory report, the Second State of Carbon Cycle Report, and others (Smith, Heath, & Hoover, 2013; Janowiak et al., 2017; Zomer, Bossio, Sommer, & Verchot, 2017; USGCRP, 2018; Bolstad & Vose, 2005). Where possible, values specific to Southeastern MA were used. Carbon pool estimation for restored wetlands was drawn from Hemes et al. (2019). The full carbon pools table can be found in Appendix D. No sensitivity analysis or calibration was performed for the carbon model because it is such a simplified model; unlike the NDR model and the Habitat Quality model, there are no model parameters that need to be tuned.

5.3.7 Running the InVEST Models

After collecting and preparing data, performing sensitivity analyses, and calibrating the models, I ran the three individual InVEST ecosystem service models (NDR, Habitat Qualiy, and Carbon Storage and Sequestration) described in the preceding sections. I used InVEST v3.10.2, and used the InVEST Python package to run the models programmatically. I ran each of the three models on all eleven of the LULC maps I generated in order to estimate the spatial distribution of ecosystem services under different combinations of cranberry farming and wetland restoration.

In general, the InVEST models use and produce data in a geospatial format. Most of the InVEST models used here produced raster output maps showing the estimated distribution of an ecosystem service across the region. Some of the models also produced vector maps that aggregated the ecosystem service at the watershed level.

5.3.8 Valuation of Ecosystem Services

In R2, I ask: *What is the estimated value associated with ecosystem services under different restoration scenarios?* The InVEST models generate modelled estimates of ecosystem services across space. In order to connect these services to their potential economic benefit for the region, I used simple ecosystem service valuation methods and heuristics to estimate the financial value that restored wetlands could bring to the region. In all cases, the estimated value indicates a one-time payment, not an annual payment. Value estimation was not performed for the Habitat Quality model due to the general nature of the output of this model.

Water Purification Service Valuation

I used a simple "replacement cost" method to estimate the value of water purification services as estimated by the NDR model. For both nitrogen and phosphorus, I calculated the difference in exported nitrogen and phosphorus, in $\frac{kg}{pixel*year}$, between the 100% farming and 100% restoration scenarios. These values represented the expected reduction in nitrogen or phosphorus under a wetland restoration scenario.

From the literature, I found estimates of the cost per kilogram of removing nitrogen and phosphorus through traditional wastewater management systems. For nitrogen, a traditional wastewater management system costs $1,589 per kilogram of removed nitrogen; for phosphorus, a traditional wastewater management system costs $118 per kilogram of removed phosphorus. The nitrogen cost was sourced from a 2010 Cape Code Watershed report compiled by Preserve Cape Code (2010), while the phosphorus removal cost came from a white paper by Bashar et al. (2018). Both numbers were adjusted for inflation.

These replacement cost estimates were multiplied by the difference in nutrient export at each pixel to calculate a spatially-explicit estimate of the monetary value that could be generated through reduced nutrient export under a restoration scenario.

Carbon Sequestration Service

As in the water purification case, I wanted to look at the difference in carbon storage between the 100% farming and 100% restoration scenarios. To do so, I subtracted the modelled carbon storage for the present-day, 100% farming scenario from the modelled carbon storage for a hypothetical 100% restoration scenario 10 years in the future. This difference in carbon storage is the estimated carbon sequestration over time.

To assign a financial value to this carbon sequestration, I used a conservative estimate of the social cost of carbon: $20 per metric ton. The social cost of carbon is "an estimate, in dollars, of the economic damages that would result from emitting one additional ton of carbon dioxide into the atmosphere" (Rennert & Kingdon, 2019). Values for the social cost of one ton of carbon range from $1 to more than $200, lending significant uncertainty to this valuation process. Nonetheless, the goal of this research was not to improve upon social cost of carbon estimates, but rather to build knowledge around how towns or farmers could generate real revenue from wetland restorations.

5.3.9 Restoration Prioritization Index

In R3, I ask: *Which cranberry bogs should be prioritized for restoration?* To address this question, I designed and computed a *Restoration Prioritization Index* that combined the results of the ecosystem service modeling and valuation into a high-level, user-friendly format that could be of use to decision-makers at the town or regional level.

To do so, I adapted a "hotspots" identification algorithm from Blumstein and Thompson (2015) to develop a restoration prioritization index for cranberry bogs. For each ecosystem service, I calculated the difference in ecosystem service between the 100% farming scenario and the 100% restoration scenario. Then for each ecosystem service, I segmented each ecosystem service layer into 20% bins, and mapped values in those bins to the 0 to 1 range. That is, the top 20% of values were mapped to 1, the next 20% of values to 0.8, the next 20% of values to 0.6, and so on. For the NDR model, the "top" (or best) 20% of values were actually the bottom 20% of values, which had the greatest negative difference between a hypothetical restoration scenario and the present, indicating the greatest reduction in nutrient export.

At this point, each of the ecosystem service layers had values in the range of 0-1. I added these files together so that every pixel had a "score" between 0-4, then calculated the average of pixel values within each cranberry bog, indicating how beneficial that bog would potentially be if it were to undergo a wetland restoration. This average score was then rescaled to the 0 to 100 range to generate a priority ranking to each bog, with higher numbers indicating greater restoration priority.

5.3.10 Socioeconomic Contextualization

The final piece of analysis conducted for this portion of the dissertation was to use local and regional socioeconomic data to contextualize the potential value of ecosystem services from cranberry bog wetland restorations. This work involved aggregating the potential value from ecosystem services at the cranberry bog and town level. Because I was not able to perform a valuation of the habitat quality ecosystem service, this contextualization work only takes into account potential value from water purification (the NDR model) and carbon sequestration. The following metrics were computed:

- Bog Level:
  - *Potential Value*: The potential value of water purification and carbon sequestration were summed at each point then aggregated across the area of each cranberry farm.
  - *Assessed value comparison*: The assessed value of each parcel containing a current cranberry farm was retrieved from the MassGIS Interactive Property Map (Mass.gov, n.d.). The potential value of a wetland restoration was computed as a percentage of the total assessed value of the parcel. Notably, most parcels were larger in area than the cranberry farm they contained; many parcels contained uplands or residential space in addition to the cranberry farm. However, the relative size of cranberry farms and their surrounding parcels varied widely; some farms made up the majority of the parcel area, while other farms represented only a small fraction of the parcel area.
- Town Level:

- *Potential Value*: The potential value of water purification and carbon sequestration were summed at each point then aggregated across every cranberry farm within a given town.
- *Percentage of annual budget*: The annual budget of each town in the region was retrieved from ClearGov.com, which scrapes budgetary data from the Massachusetts Department of Revenue (ClearGov Inc., 2022). I used the most recent budget data available, which in most cases was from FY2019, FY2020, or FY2021. The combined potential value of all wetland restorations in the town was then computed as a percentage of the town's most recent annual budget to contextualize the value wetland restorations could bring to the town.
- *Per capita value*: Using town population data drawn from MassGIS, the combined potential value of all wetland restorations in the town was computed on a per capita basis.

This socioeconomic contextualization work was largely conducted in service of the data visualization and exploration web tool, which is discussed in more detail in Chapter 6.

5.4 Results

5.4.1 NDR Model

The geospatial results for nitrogen export for the 100% farming scenario and the 100% restoration scenario are show in Figure 5-15. The corresponding geospatial results for phosphorus export are shown in Figure 5-17. In both cases, the differences in nutrient export between the two scenarios are limited to the immediate vicinity of the cranberry bogs, which makes them difficult to detect visibly. Thus, I also present Figure 5-16, which shows the *difference* in nitrogen export between the 100% farming and 100% restoration scenarios, and Figure 5-18, which shows the corresponding results for phosphorus export.

The maps in Figures 5-15 and 5-17 show, for every pixel, how much nitrogen or phosphorus coming from each pixel eventually reaches the watershed. The intuition for interpreting these maps is that darker areas with higher nutrient export are either quite close to streams, so the nutrient does not have as far to travel to reach the stream, or they are areas with a steeper slope, which means the nutrient will run down the slope more easily, or they are in areas where the land use type is not good at retaining and holding on to the nutrient.

In Figures 5-16 and 5-18, which show the difference in nutrient export between the two scenarios, darker areas represent a greater difference in nutrient export. These are areas where a wetland restoration would be particularly beneficial, because the restoration could remove a larger amount of nutrient from the system. Because my land use change analysis only involves changing the land use type of today's cranberry farms, and no other areas, the changes in nutrient export are localized to the vicinity of the cranberry bogs. This result is expected given the structure of the analysis, and makes it possible to isolate the change in ecosystem services that we might see based on a wetland restoration of a cranberry farm.

The model results suggest that under a 100% restoration scenario, there would be an estimated reduction of approximately 10,000 kilograms of nitrogen, which would be worth around $16.5M to the region, based on the valuation process described in Section 5.3.8. Towns with a high concentration of cranberry bogs were estimated to experience a 5-10% reduction in annual nitrogen export. For phosphorus, the model results estimate that under a 100% restoration scenario, there would be an estimated reduction of approximately 2,000 kilograms of phosphorus, worth around $200,000 to the region. Towns with a high concentration of cranberry bogs were estimated to experience a 15-30% reduction in annual phosphorus export. In both cases, the estimated value indicates a one-time payment, not an annual payment. Taken together, these estimates help establish a range for potential nutrient removal and help develop intuition about the distribution and potential value of wetland restorations in the area.

5.4.2 Habitat Quality Model

The geospatial results for habitat quality for the 100% farming scenario and the 100% restoration scenario are show in Figure 5-19. These maps visualize the relative habitat quality score between 0 and 1 for every pixel, with higher scores indicating areas of higher habitat quality.

As in the NDR case, it can be difficult to visually detect the difference between the two maps in Figure 5-19 due to the detailed nature of the maps. Thus, Figure 5-20 shows the difference in habitat quality score between the 100% farming and 100% restoration scenarios.

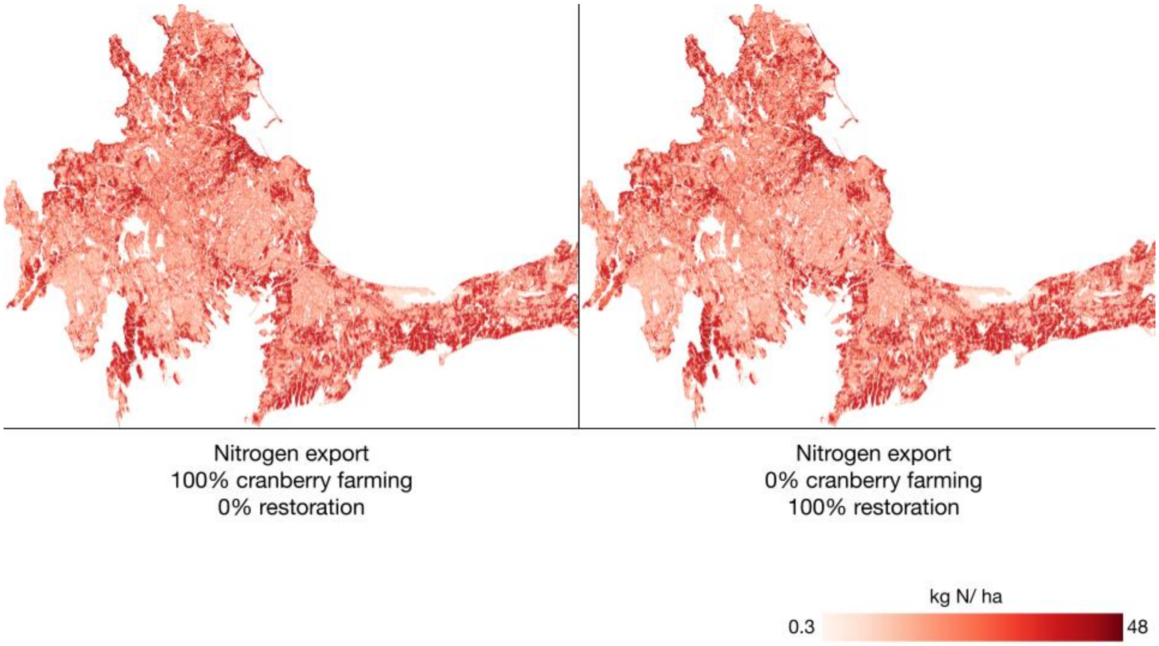


Figure 5-15: NDR nitrogen model results for 100% farming and 100% restoration scenarios

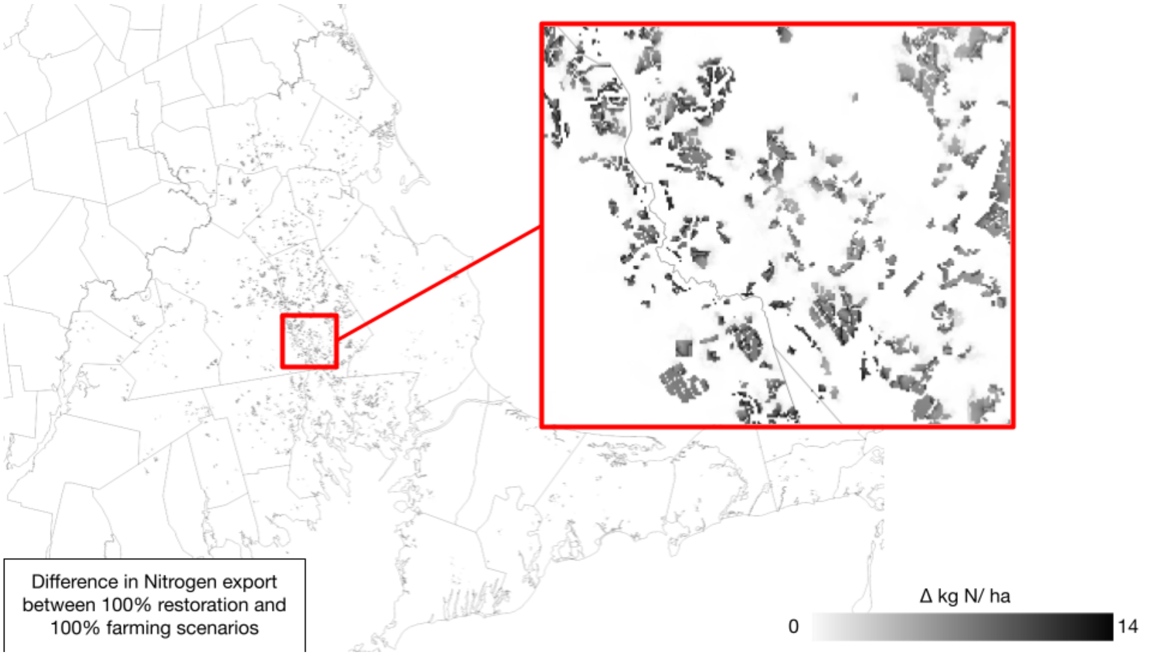
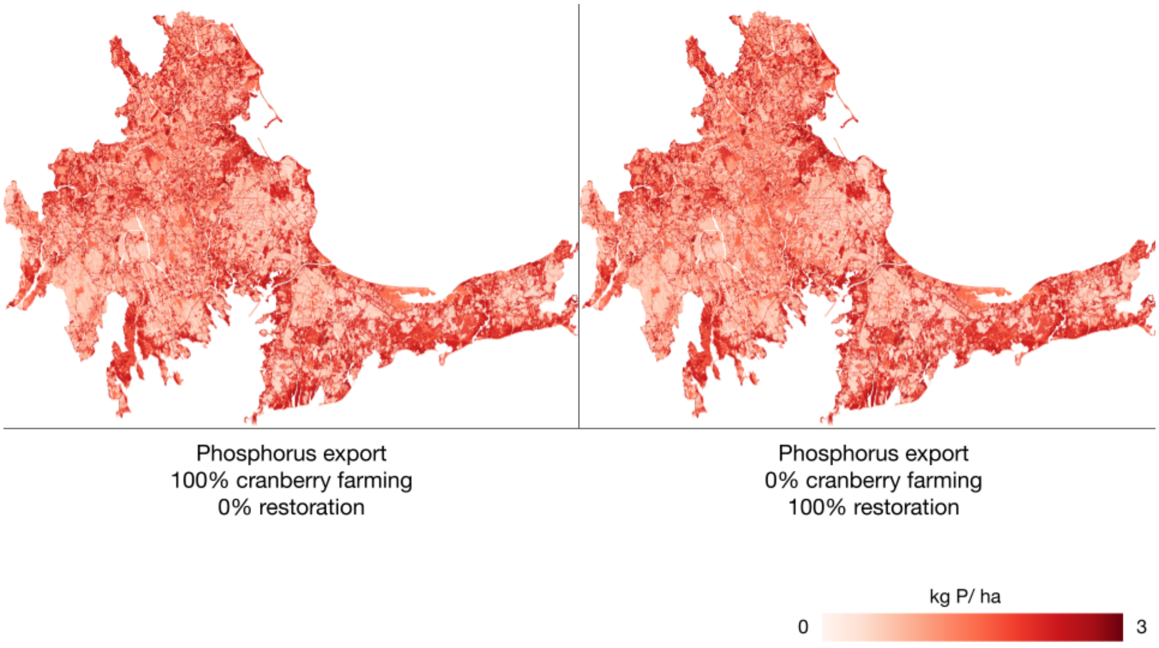


Figure 5-16: Difference in nitrogen export between 100% farming and 100% restoration scenarios


Phosphorus export
100% cranberry farming
0% restoration

Phosphorus export
0% cranberry farming
100% restoration

Figure 5-17: NDR phosphorus model results for 100% farming and 100% restoration scenarios

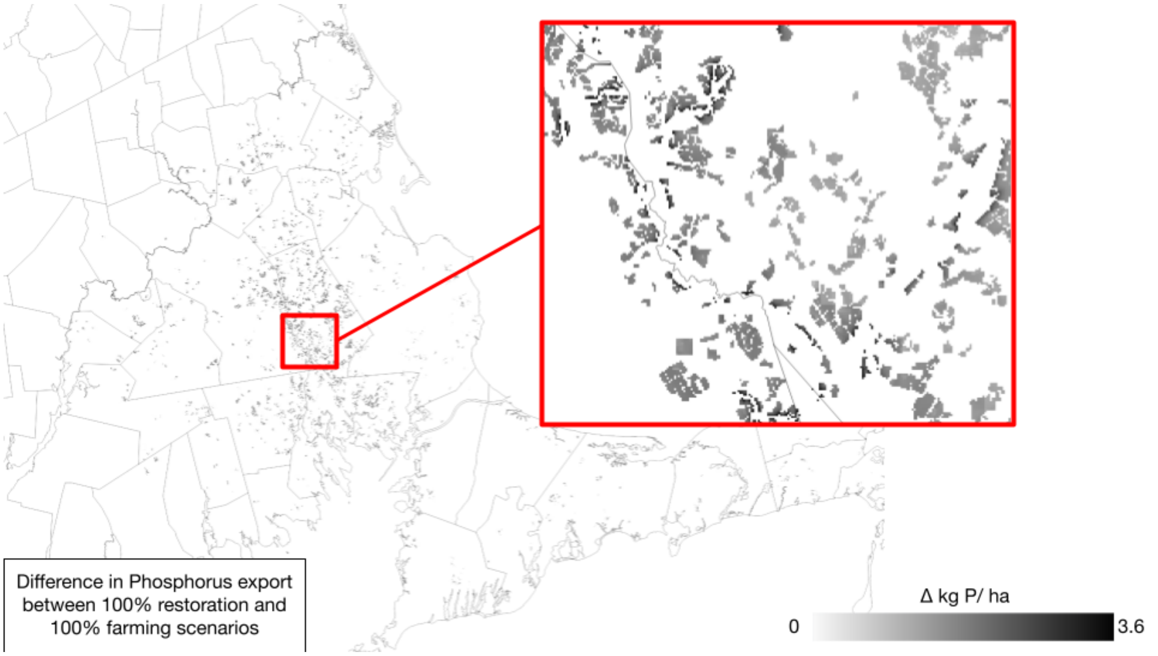


Figure 5-18: Difference in phosphorus export between 100% farming and 100% restoration scenarios

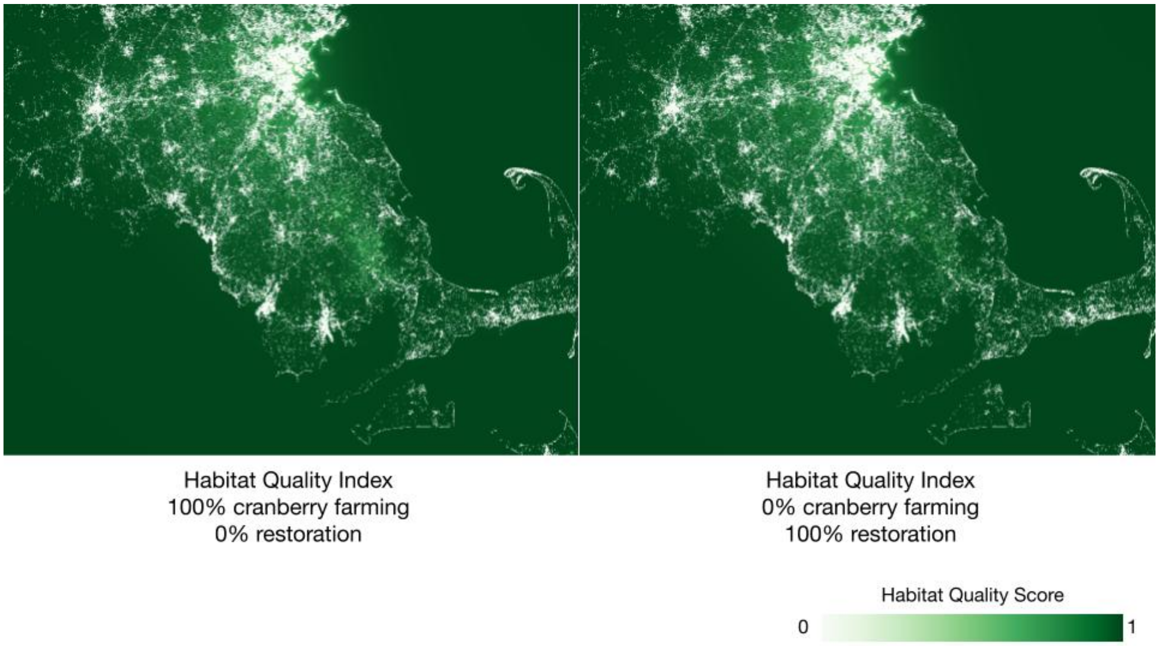
In Figure 5-20, darker areas represent a greater change in habitat quality, which is beneficial because it indicates greater support for biodiversity in these areas. It is interesting to note that differences in habitat quality score are *not* fully localized to the restored wetland areas. Instead, areas adjacent to the newly restored wetlands all have improved habitat quality scores. This effect is an artifact of the model, which calculates habitat quality based on the distance to threats like agriculture or development. Thus, when agriculture is removed from the landscape, there is a spillover effect on the quality of habitats adjacent to the restored wetland.

5.4.3 Carbon Storage and Sequestration Model

The geospatial results for carbon storage for the 100% farming scenario and the 100% restoration scenario are show in Figure 5-21. These maps visualize the estimated stored carbon at every pixel. As in the NDR and Habitat Quality cases, it can be difficult to visually detect the difference between the two maps in Figure 5-21 due to the detailed nature of the maps.

To elucidate the distinction between the result maps, Figure 5-22 shows the difference in carbon storage, also called carbon sequestration, between the 100% farming and 100% restoration scenarios. Notably, the amount of sequestration is uniform across all cranberry bogs. This result is an artifact of the highly simplified model, which treats all areas within a single land use the same way. Thus, this model unfortunately does not make it possible to distinguish between or prioritize wetland restorations based on potential carbon sequestration. Instead, it simply helps approximate the overall carbon storage that might be expected in the region.

The model results suggest that under a 100% restoration scenario, over ten years, there could be around 240,000 tons of carbon sequestered in the restored wetland areas. It is interesting to consider the financial value of sequestration, because carbon sequestration is the ecosystem service where there is the most mainstream familiarity with associating a dollar value with a ton of carbon. Based on the valuation process described in Section 5.3.8, it is estimated that if 40% of cranberry farm acres were restored, the potential carbon storage sequestration in those areas would be worth about $2M to the region. If every cranberry bog in the region were restored, the potential carbon storage sequestration would be worth about $4.8M to region. These estimated valuations most likely represent one-time payments, not annual payments; however, there are a variety of payout structures in voluntary carbon markets,


Habitat Quality Index
100% cranberry farming
0% restoration

Habitat Quality Index
0% cranberry farming
100% restoration

Figure 5-19: Habitat Quality model results for 100% farming and 100% restoration scenarios

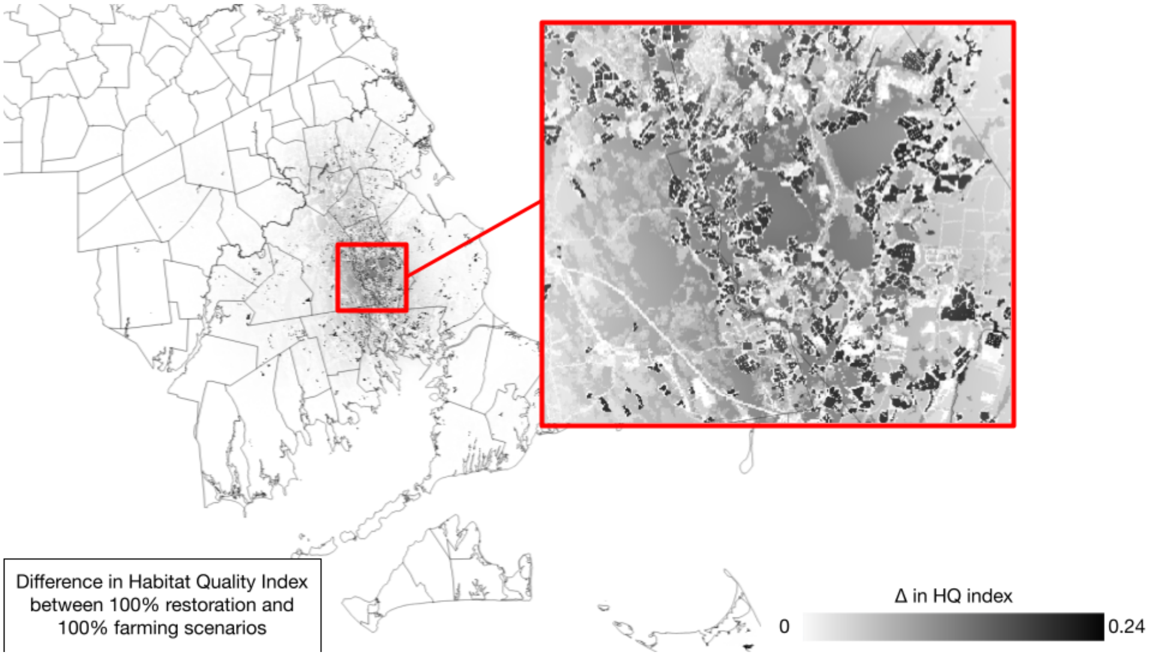
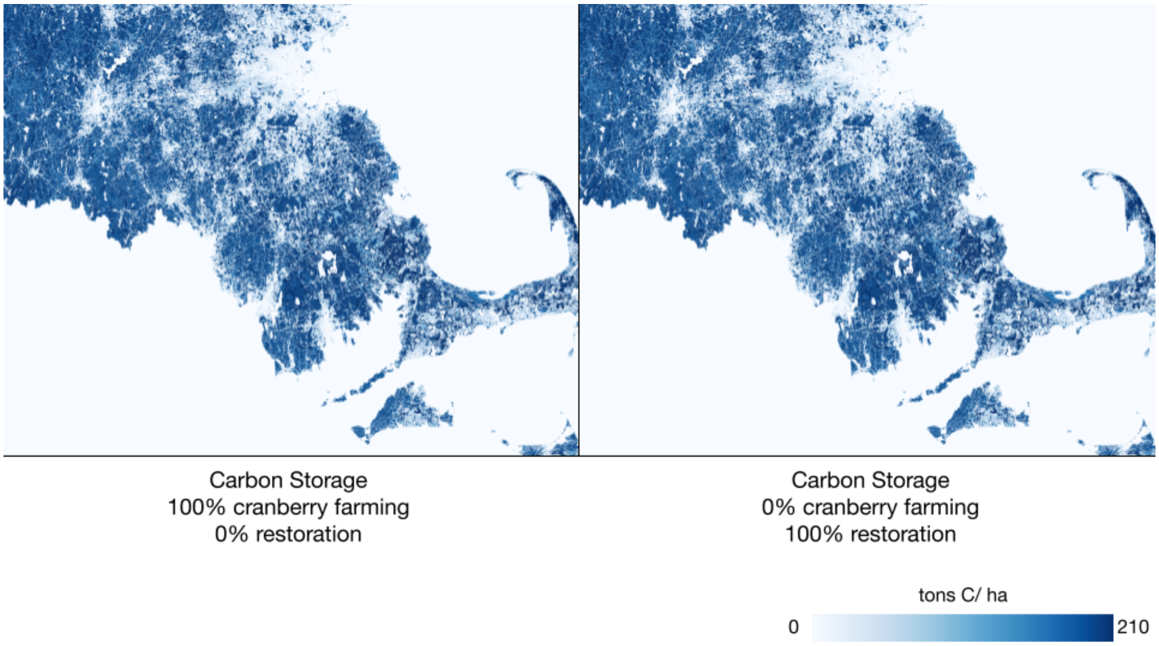

Difference in Habitat Quality Index between 100% restoration and 100% farming scenarios

Figure 5-20: Difference in Habitat Quality index between 100% farming and 100% restoration scenarios


Carbon Storage
100% cranberry farming
0% restoration

Carbon Storage
0% cranberry farming
100% restoration

Figure 5-21: Carbon Storage and Sequestration model results for 100% farming and 100% restoration scenarios

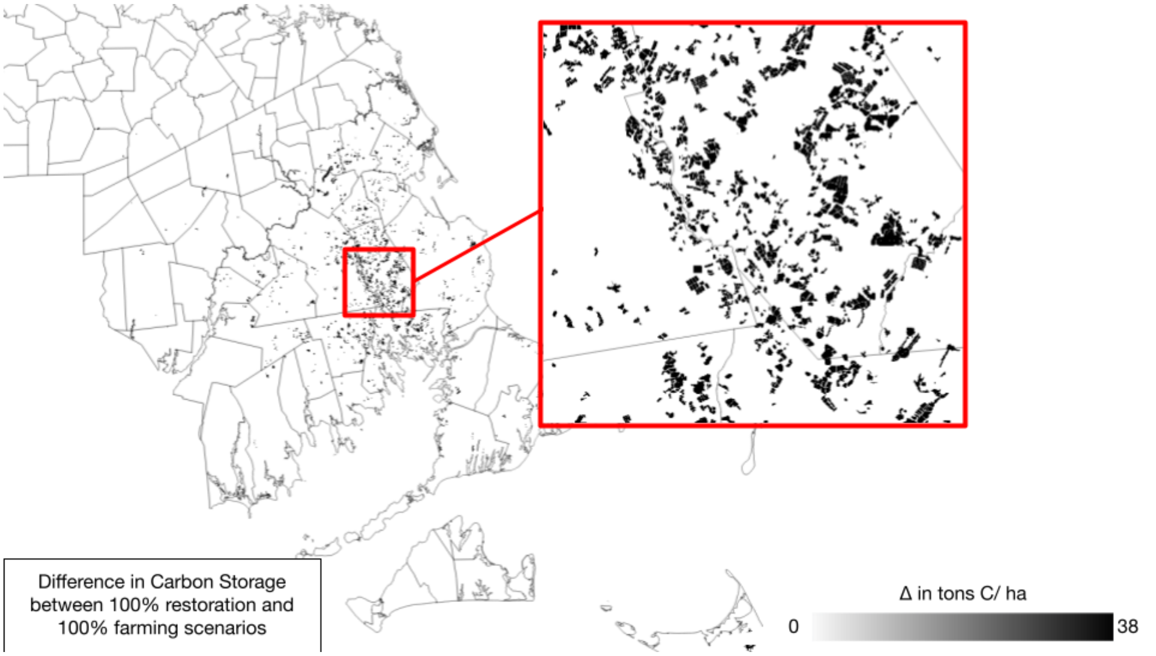


Figure 5-22: Carbon sequestration estimated due to transition from 100% farming to 100% restoration scenario

and it is possible that payments could be disbursed over time.

This valuation uses a very conservative estimate of the social cost of carbon. Given the wide range of values for the social cost of carbon, which Rennert and Kingdon (2019) give as $1-$200, the estimated financial value of carbon sequestration in the region also varies significantly. Though there is significant uncertainty in this estimate, given the profusion of carbon markets and credit programs, generating regionally-specific estimates of the value of carbon sequestration is an important way to build knowledge around how towns or farmers could link wetland restorations to real financial incentives.

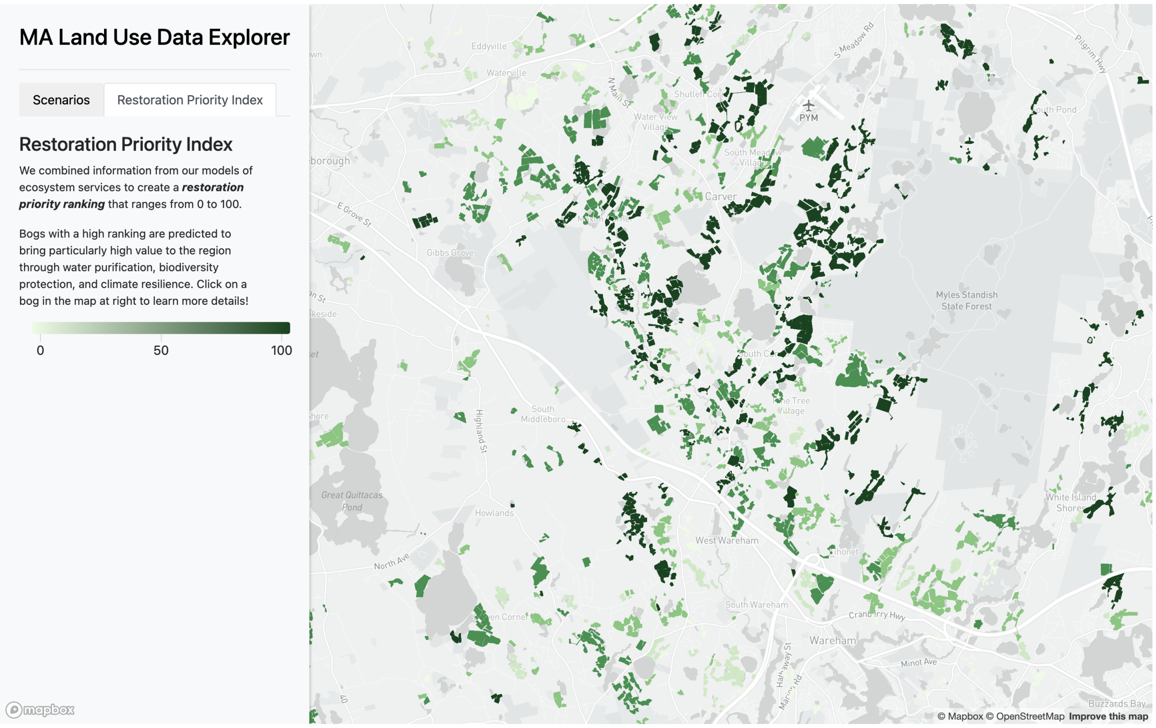
5.4.4 Restoration Prioritization Index

A visualization of the Restoration Prioritization Index is presented in Figure 5-23. This figure is drawn from the data visualization and exploration web tool, which is discussed further in Chapter 6. Cranberry farms shaded in darker green have a higher restoration priority, whereas farms shaded in lighter green have relatively lower priority, based on the weighted combination of ecosystem services that contribute to the index. The index is meant to be a tool that a high-level decision-maker, such as a town or state administrator, could use to identify bogs where a wetland restoration would have relatively higher value in terms of ecosystem services. While it was outside the scope of this research to interrogate the ranking distribution and implications of the index, further analysis of the prioritization ranking would likely yield interesting and relevant insights.

5.4.5 Socioeconomic Contextualization

The goal of the socioeconomic contextualization analysis was to position the ecosystem service valuation in relatable and relevant terms. This analysis is displayed in a more dynamic and interactive format in the data visualization and exploration web tool, which is discussed further in Chapter 6.

Basic statistics for each of the metrics introduced in Section 5.3.10 are presented in Table 5.5. The results suggest there is wide variation in the potential financial benefit that wetland restorations could bring to a town. For towns with a large number and high concentration



MA Land Use Data Explorer

Scenarios | Restoration Priority Index

Restoration Priority Index

We combined information from our models of ecosystem services to create a ***restoration priority ranking*** that ranges from 0 to 100.

Bogs with a high ranking are predicted to bring particularly high value to the region through water purification, biodiversity protection, and climate resilience. Click on a bog in the map at right to learn more details!

Figure 5-23: Visualization of Restoration Prioritization Index

of cranberry farms, such as Carver, Rochester, and Plympton, the potential value of wetland restorations in the town could be quite significant. For other towns with lower concentrations of cranberry farms, restorations would likely not have a large impact on the financial situation of the town, but could still be relevant at the scale of a neighborhood or family.

Analysis Level	Metric	Minimum	Maximum	Median
Bog level	Potential Value ($)	$190	$266,833	$9,958
Bog level	Assessed value comparison (%)	0%	52,774%	5%
Town level	Potential Value ($)	$594	$5,760,283	$95,762
Town level	Percentage of annual budget (%)	0%	14%	0.15%
Town level	Per capita value (%/pp)	$0	$500	$6

Table 5.5: Basic statistics for socioeconomic contextualization metrics

As in the case of the restoration prioritization index, it was outside the scope of this research to conduct further analysis of these rankings and metrics, but it is likely that doing so would yield additional interesting and relevant insights.

5.5 Discussion

The research in this portion of the dissertation aimed to answer three research questions concerning the quantity and distribution of ecosystem services under different wetland restoration scenarios, the potential value associated with those ecosystem services, and the resulting priority order for restorations, given those ecosystem services. To address these questions, I first designed an analysis approach using the EVDT framework, which allowed me to map out which data were needed and understand how the different models and data I used would fit together. Working within the EVDT framework, I generated different land use scenarios with random distributions of wetland restoration, applied three different InVEST ecosystem services models to these potential land use scenarios, used economic heuristics to estimate the value of these ecosystem services, and then developed a prioritization index and socioeconomic contextualization metrics to help communicate this analysis to stakeholders. As far as I am aware, this work is the first time InVEST had been applied in the context of the MA cranberry industry with respect to ecosystem services and wetland restoration.

Given the framing of the Systems Architecture Framework and EVDT, the research presented in this section was largely focused on producing estimates of ecosystem services and developing metrics that would be meaningful to stakeholders, instead of interrogating the meaning and accuracy of the metrics themselves. That said, this work did prompt reflection on the process of working with InVEST, and on methods for addressing and managing uncertainty.

5.5.1 Reflections on Applying the InVEST Model to Southeastern MA

The InVEST ecosystem service models were selected for this work because they are open-source, well-documented and well-supported, location-agnostic, and relatively accessible to non-experts. That said, in the course of developing and applying InVEST in the context of this research, several limitations of the software became clear.

One limitation is that the InVEST models are heavily simplified. For example, the carbon storage and sequestration model treats all areas of the same land use type identically, and does not account for changes in carbon storage within a single land use type over time. These are gross simplifications of the carbon cycle, and do cast some doubt on the accuracy of the models. In some cases, the simple nature of the model made it difficult to actually distinguish between the restoration potential of different bogs. That said, there is an opportunity to inject more precision into the modeling process via more detailed data inputs. For example, instead of treating all cranberry farms as the same land use type, it would be possible to run the model with two or more classes of cranberry farms, based on their soil or hydrology type. Assembling input data that captures this nuance, however, is a challenging and time-consuming process that was out of the scope of this dissertation.

These critiques aside, there are benefits to working with a simple model. InVEST's simplicity meant it was relatively easy to get three separate models up and running, even without deep subject-area expertise. When integrating the results from the different models, the relative simplicity of the models made it easier to troubleshoot, develop intuition for how the models worked, and ensure successful integration of results. Thus, I believe the most relevant question as it relates to model simplicity is: "What level of abstraction is acceptable for this use case?" I would argue that continuing to use the InVEST models but injecting them with more fine-grained data inputs would strike an acceptable balance between simplicity and accuracy in the modeling process.

Another major challenge of working with InVEST was the difficulty of assembling and generating the user-defined data input tables for the models, including the biophysical table for the NDR model, the threats and sensitivity tables for the habitat quality model, and the carbon pools table for the carbon model. The challenge was partially that assembling these tables required a time-consuming literature search. More fundamentally, though, sometimes the values I was looking for did not exist. For example, these is very little published data around the carbon storage in restored cranberry bogs. Sometimes I was able to find values that were specific to restored wetlands, but other times I had to make the assumption that restored wetlands have the same carbon storage and biophysical properties as native wetlands, even though there is nuanced research to the contrary. This challenge speaks to the need for continuing both fundamental restoration science and ecosystem service modeling, with the hope that these efforts will further converge in the future.

5.5.2 Addressing Estimate Uncertainty

One major gap in this research effort was characterizing the uncertainty of the InVEST models. There is significant uncertainty in the results of the InVEST modeling, and though it unfortunately fell outside the scope of this dissertation to directly calculate uncertainty, doing so is a vital next step. To do so, I would propose adapting the approach discussed in Hamel and Guswa (2015). Briefly, this method generates a range of potential input data through a literature search. For example, if the input in question were the average nitrogen loading rate of a restored cranberry bog, I would retrieve a range of possible values for this metric from a literature search. In essence, I would create three biophysical tables: one containing the minimum value for the nitrogen loading rate, one with the median value for the loading rate, and one with the maximum value for the loading rate. I would then run the InVEST model on all three of the tables, to propagate the uncertainty through the model. The range of model outputs would represent a likelihood range that the actual value would be likely to fall within. In Section 6.4.2, I discuss how this likelihood range could be communicated visually to address uncertainty from a user experience perspective.

As in the discussion around model simplicity, it is important to consider how much uncertainty is acceptable in the model estimates. Some applications, such as when determining payouts for an ecosystem service, or ensuring compliance with environmental quality standards, may require a high degree of precision in model results. On the other hand, there may be other settings where it is good enough for the model to accurately predict directional relationships instead of precisely accurate numbers. For example, when comparing two bogs for their restoration potential, it may be enough to know that one bog has higher carbon sequestration capacity than the other, instead of producing exact estimates for the amount of carbon each bog could sequester. Thoughtful reflection on this question should guide the approach towards uncertainty calculation.

Chapter 6

Development and Evaluation of a Web-Based Geospatial Data Visualization Tool for Land-Use in the MA Cranberry Industry

6.1 Project Overview

A key component of the EVDT framework is an interactive and dynamic user-interface that visualizes data and communicates analysis from other parts of the framework. In this portion of the thesis, I describe the development of a web-based geospatial data visualization tool that presents the results of the modeling work in Chapter 5 in a user-friendly, accessible format. Additionally, I conduct a user study with key industry stakeholders to gauge the usability and potential utility of the web-based tool. The goal of this work was to create a user-friendly front-end for the ecosystem service analysis, thereby closing the loop between the quantitative analysis and modeling performed under the EVDT framework and the stakeholders for whom the analysis was conducted.

6.2 Research Questions

This portion of the thesis research was driven by the following research questions:

- R1: How can the results of the modeling work in Chapter 5 be presented in a way that is engaging, accessible, and dynamic?
- R2: How do key stakeholders in the industry respond to the results of these models and the way the data is being presented?

6.3 Research Design and Methods

To address the above research questions, I developed a web-based data exploration and scenario tool, drawing on best practices and design principles from data visualization tools built by J. B. Reid and Wood (2020a) and Climate Interactive (2022). The key principles that drove the design and functionality of the web tool were: an explicit focus on geospatial data; a focus on interactive scenario planning; and a responsive and dynamic interface. To evaluate the usability and potential utility of the web-tool, I drew on usability evaluation practices from Jordan et al. (1996) to conduct a stakeholder survey. By applying qualitative coding to the results of the usability survey, I was able to identify and reflect on the strengths and weaknesses of the web-based data exploration tool, and propose a future research agenda that can build upon the research presented in this dissertation.

6.3.1 Design and Development of Web-Based Data Exploration Tool

The development of this web-based data visualization and exploration tool took place alongside the modeling work described in Chapter 5. Development followed a spiral development pattern, with iterative cycles of design, development, and informal user feedback, culminating in a more formal usability study, which is described in Section 6.3.2. The site aims to embody three key design principles, derived from best-in-class geospatial exploration tools, such as the En-ROADS climate simulator and user interfaces developed for other EVDT implementations. These principles are:

- There is an explicit focus on *geospatial data*, with maps and map-based data central to the user experience.
- User interaction with the site is driven by *scenario and policy exploration*. Users can toggle between different scenarios to see the outcomes of different policies.
- The site is highly *responsive*. Users are able to interact with data through several different design affordances.

The web application is written in Python and uses the Flask framework. Geospatial data were generated using the InVEST models, as described in Chapter 5, then hosted in Mapbox, and styled through the Mapbox API. The web application is hosted on Heroku. The key features of the web-based data explorer tool are as follows.

Land Use Scenarios Explorer

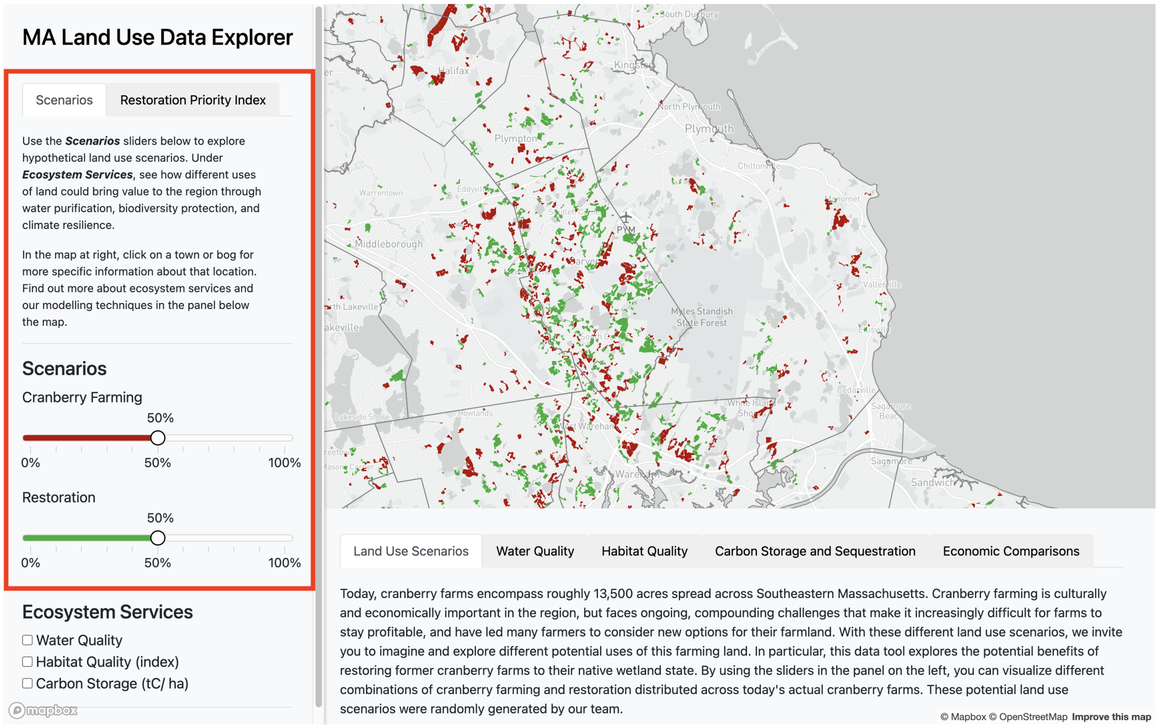
The "Land Use Scenarios Explorer", highlighted in Figure 6-1, allows users to toggle between different distributions of cranberry farming and wetland restoration using a pair of sliders. When the sliders are moved, the geospatial data in the map panel on the right adjusts to reflect the new distribution of farming and restoration.

Ecosystem Service Layers

The "Ecosystem Service Layers", highlighted in Figure 6-2, are the set of check-box controls and corresponding geospatial map layers that allow users to view the results of the InVEST ecosystem service models. Users can turn "on" or turn "off" the results of the different ecosystem service models using the checkboxes, and the modelled distribution of ecosystem service will appear in the map panel at right. The ecosystem service data layers can be stacked, as shown in the figure, and are specific to the LULC scenario currently selected by the sliders.

Information Panels

The "Information Panels", highlighted in Figure 6-3, are the set of five panels at the bottom of the web application. The panels contain informational text about the land use scenarios, the three modelled ecosystem services, and the socioeconomic analysis. The writing in the panels



MA Land Use Data Explorer

Use the ***Scenarios*** sliders below to explore hypothetical land use scenarios. Under ***Ecosystem Services***, see how different uses of land could bring value to the region through water purification, biodiversity protection, and climate resilience.

In the map at right, click on a town or bog for more specific information about that location. Find out more about ecosystem services and our modelling techniques in the panel below the map.

Scenarios

Cranberry Farming: 50%

Restoration: 50%

Ecosystem Services

☐ Water Quality
☐ Habitat Quality (index)
☐ Carbon Storage (tC/ ha)

Today, cranberry farms encompass roughly 13,500 acres spread across Southeastern Massachusetts. Cranberry farming is culturally and economically important in the region, but faces ongoing, compounding challenges that make it increasingly difficult for farms to stay profitable, and have led many farmers to consider new options for their farmland. With these different land use scenarios, we invite you to imagine and explore different potential uses of this farming land. In particular, this data tool explores the potential benefits of restoring former cranberry farms to their native wetland state. By using the sliders in the panel on the left, you can visualize different combinations of cranberry farming and restoration distributed across today's actual cranberry farms. These potential land use scenarios were randomly generated by our team.

Figure 6-1: Web application screenshot highlighting Land Use Scenarios Explorer

our modelling techniques in the panel below the map.

Scenarios

Cranberry Farming: 50%

Restoration: 50%

Ecosystem Services

☑ Water Quality
 ☑ Annual Nitrogen Export (kg/ ha)
  ☐ Value relative to baseline ($/ ha)

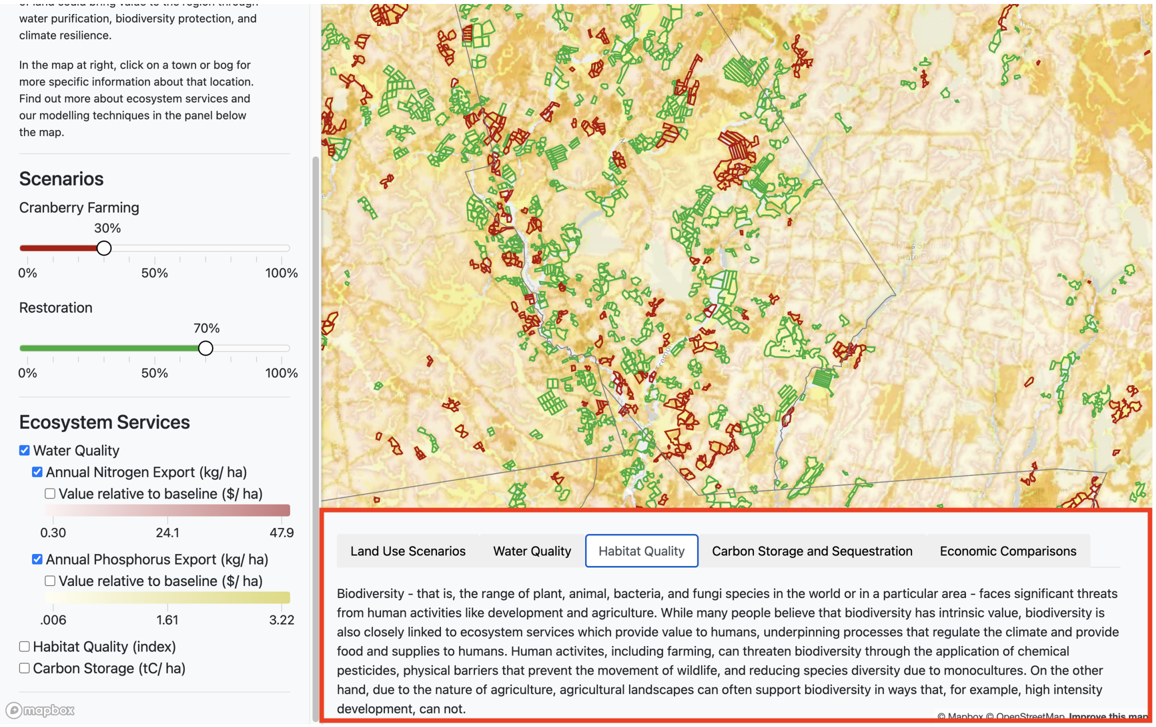
 ☑ Annual Phosphorus Export (kg/ ha)
  ☐ Value relative to baseline ($/ ha)

☑ Habitat Quality (index)

☑ Carbon Storage (tC/ ha)
 ☐ Value relative to baseline

Today, cranberry farms encompass roughly 13,500 acres spread across Southeastern Massachusetts. Cranberry farming is culturally and economically important in the region, but faces ongoing, compounding challenges that make it increasingly difficult for farms to stay profitable, and have led many farmers to consider new options for their farmland. With these different land use scenarios, we invite you to imagine and explore different potential uses of this farming land. In particular, this data tool explores the potential benefits of restoring former cranberry farms to their native wetland state. By using the sliders in the panel on the left, you can visualize different combinations of cranberry farming and restoration distributed across today's actual cranberry farms. These potential land use scenarios were randomly generated by our team.

Figure 6-2: Web application screenshot highlighting Ecosystem Service Layers is intended to be simple, digestible, and accessible to the lay-person who may not have much background in restoration or ecology.



water purification, biodiversity protection, and climate resilience.

In the map at right, click on a town or bog for more specific information about that location. Find out more about ecosystem services and our modelling techniques in the panel below the map.

Scenarios

Cranberry Farming: 30%

Restoration: 70%

Ecosystem Services

☑ Water Quality

☑ Annual Nitrogen Export (kg/ ha)

☐ Value relative to baseline ($/ ha)

☑ Annual Phosphorus Export (kg/ ha)

☐ Value relative to baseline ($/ ha)

☐ Habitat Quality (index)

☐ Carbon Storage (tC/ ha)

Biodiversity - that is, the range of plant, animal, bacteria, and fungi species in the world or in a particular area - faces significant threats from human activities like development and agriculture. While many people believe that biodiversity has intrinsic value, biodiversity is also closely linked to ecosystem services which provide value to humans, underpinning processes that regulate the climate and provide food and supplies to humans. Human activites, including farming, can threaten biodiversity through the application of chemical pesticides, physical barriers that prevent the movement of wildlife, and reducing species diversity due to monocultures. On the other hand, due to the nature of agriculture, agricultural landscapes can often support biodiversity in ways that, for example, high intensity development, can not.

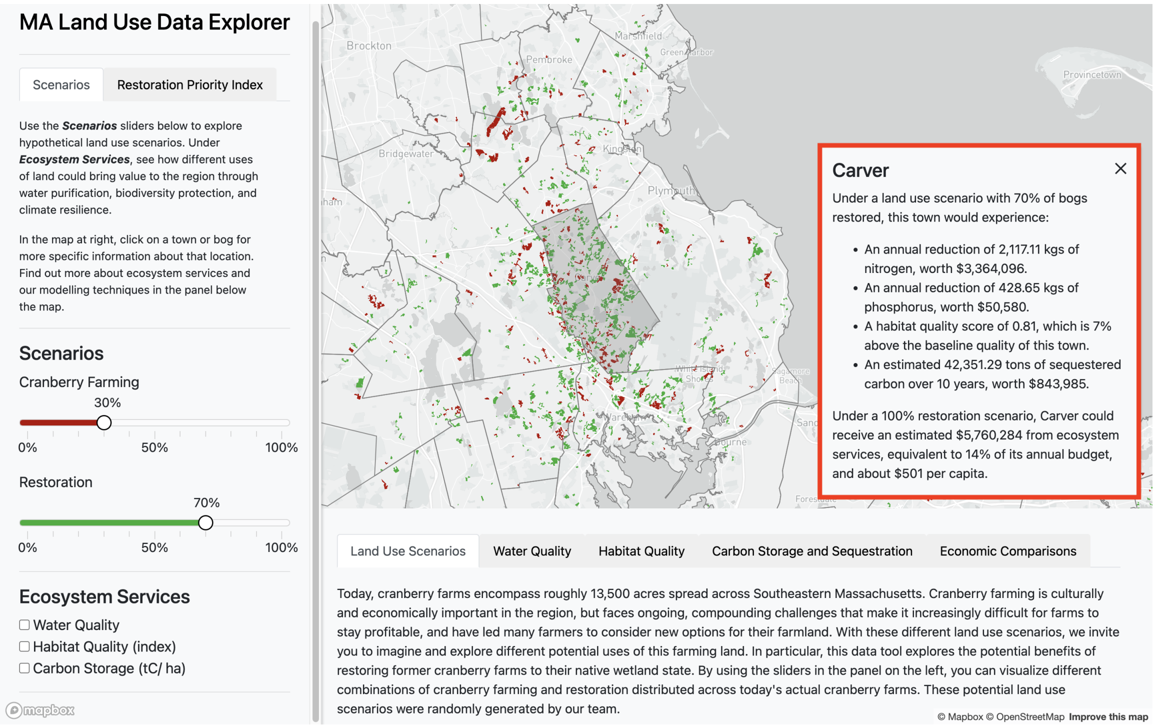
Figure 6-3: Web application screenshot highlighting Information Panels

Town-Level Socioeconomic Analysis

The "Town-Level Socioeconomic Analysis" pop-up box, highlighted in Figure 6-4, is the information box containing socioeconomic contextualization metrics for the town that is selected in the map panel. The metrics shown in the box are specific to the LULC scenario currently selected by the sliders. The information in the box shares estimates of the potential amount and value of different ecosystem services from wetland restoration in that town under the selected land use scenario. The pop-up box also displays metrics that compare the potential value from ecosystem services to the town's budget and population.

Bog-Level Socioeconomic Analysis

The "Bog-Level Socioeconomic Analysis" pop-up box, highlighted in Figure 6-5, is the information box containing socioeconomic contextualization metrics for the individual cranberry



MA Land Use Data Explorer

Scenarios | Restoration Priority Index

Use the ***Scenarios*** sliders below to explore hypothetical land use scenarios. Under ***Ecosystem Services***, see how different uses of land could bring value to the region through water purification, biodiversity protection, and climate resilience.

In the map at right, click on a town or bog for more specific information about that location. Find out more about ecosystem services and our modelling techniques in the panel below the map.

Scenarios

Cranberry Farming

30%

0% 50% 100%

Restoration

70%

0% 50% 100%

Ecosystem Services

☐ Water Quality

☐ Habitat Quality (index)

☐ Carbon Storage (tC/ ha)

Carver

Under a land use scenario with 70% of bogs restored, this town would experience:

- An annual reduction of 2,117.11 kgs of nitrogen, worth $3,364,096.
- An annual reduction of 428.65 kgs of phosphorus, worth $50,580.
- A habitat quality score of 0.81, which is 7% above the baseline quality of this town.
- An estimated 42,351.29 tons of sequestered carbon over 10 years, worth $843,985.

Under a 100% restoration scenario, Carver could receive an estimated $5,760,284 from ecosystem services, equivalent to 14% of its annual budget, and about $501 per capita.

Land Use Scenarios | Water Quality | Habitat Quality | Carbon Storage and Sequestration | Economic Comparisons

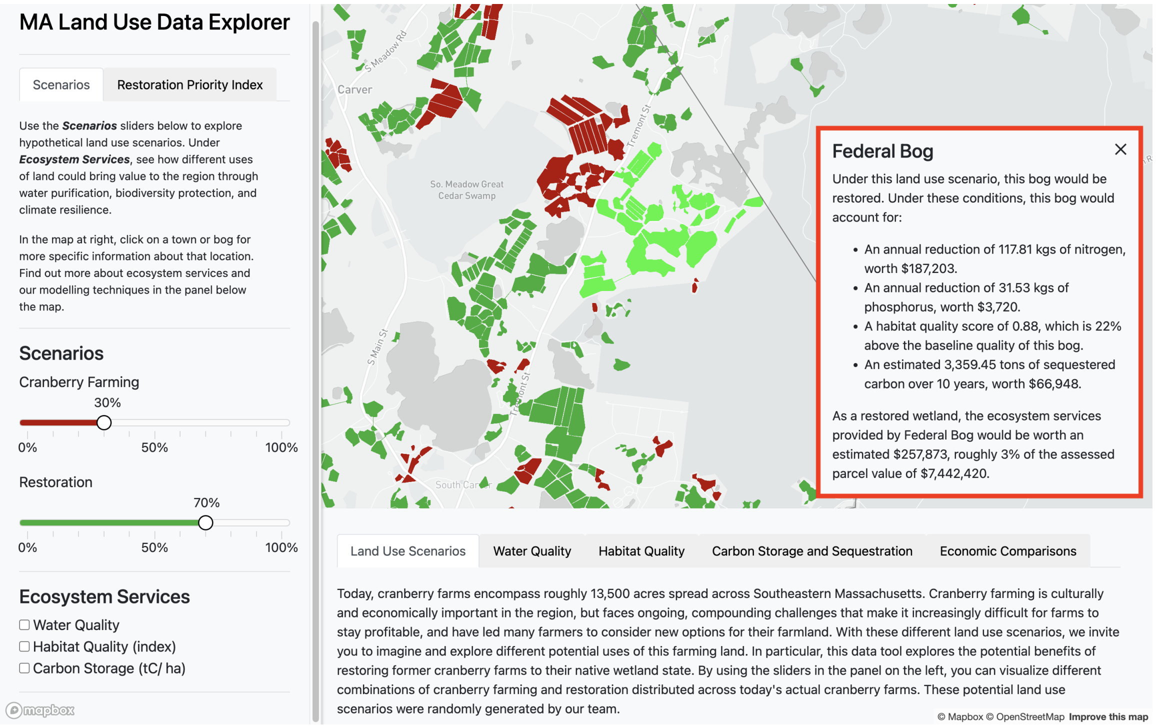
Today, cranberry farms encompass roughly 13,500 acres spread across Southeastern Massachusetts. Cranberry farming is culturally and economically important in the region, but faces ongoing, compounding challenges that make it increasingly difficult for farms to stay profitable, and have led many farmers to consider new options for their farmland. With these different land use scenarios, we invite you to imagine and explore different potential uses of this farming land. In particular, this data tool explores the potential benefits of restoring former cranberry farms to their native wetland state. By using the sliders in the panel on the left, you can visualize different combinations of cranberry farming and restoration distributed across today's actual cranberry farms. These potential land use scenarios were randomly generated by our team.

Figure 6-4: Web application screenshot highlighting Town-Level Socioeconomic Analysis

farm bog that is selected in the map panel. The metrics shown in the box are specific to the LULC scenario currently selected by the sliders. The information in the box shares estimates of the potential amount and value of different ecosystem services if that bog were to be restored to wetland under the selected land use scenario. The pop-up box also displays metrics that compare the potential value from ecosystem services to the assessed value of the parcel that contains the bog.

Restoration Priority Index

A visualization of the "Restoration Priority Index" is highlighted in Figure 6-6. The Restoration Priority Index is a computed index meant to be a tool that high-level decision-makers, such as town or state administrators, could use to identify bogs where a wetland restoration would have relatively higher value in terms of ecosystem services. Cranberry farms shaded in darker green have a higher restoration priority, whereas farms shaded in lighter green have relatively lower priority, based on the weighted combination of ecosystem services that contribute to the index.



Use the ***Scenarios*** sliders below to explore hypothetical land use scenarios. Under ***Ecosystem Services***, see how different uses of land could bring value to the region through water purification, biodiversity protection, and climate resilience.

In the map at right, click on a town or bog for more specific information about that location. Find out more about ecosystem services and our modelling techniques in the panel below the map.

Scenarios

Cranberry Farming: 30% (0% – 50% – 100%)

Restoration: 70% (0% – 50% – 100%)

Ecosystem Services

☐ Water Quality
☐ Habitat Quality (index)
☐ Carbon Storage (tC/ ha)

Federal Bog

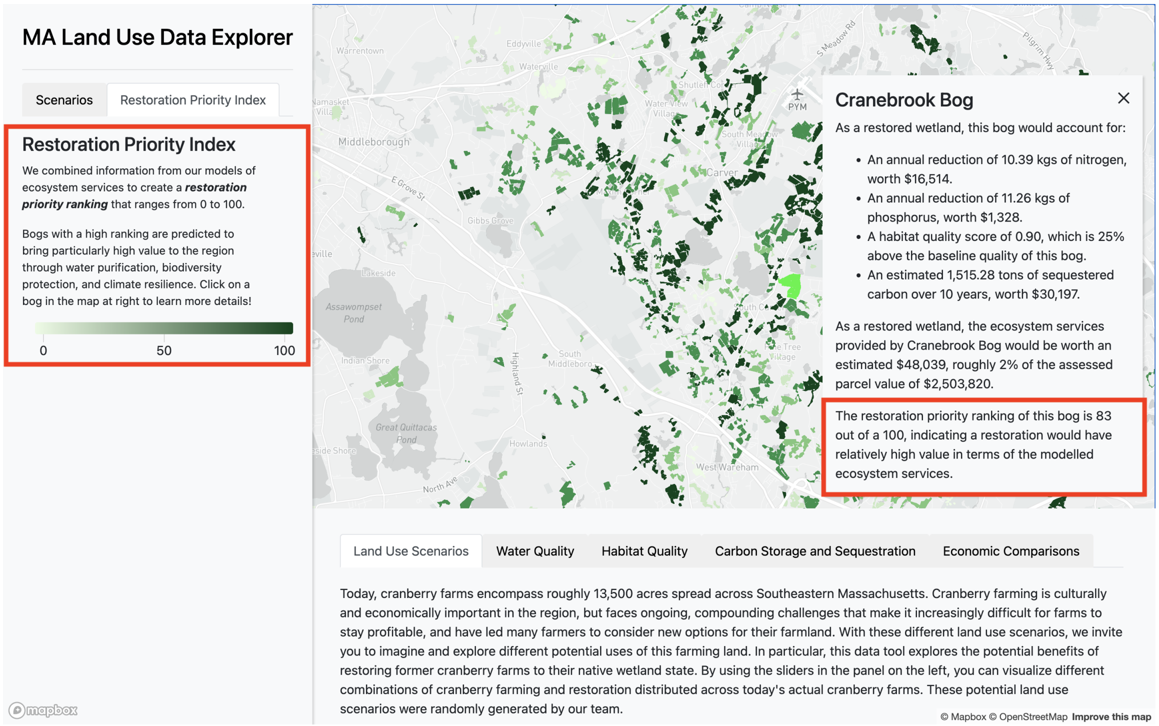
Under this land use scenario, this bog would be restored. Under these conditions, this bog would account for:

- An annual reduction of 117.81 kgs of nitrogen, worth $187,203.
- An annual reduction of 31.53 kgs of phosphorus, worth $3,720.
- A habitat quality score of 0.88, which is 22% above the baseline quality of this bog.
- An estimated 3,359.45 tons of sequestered carbon over 10 years, worth $66,948.

As a restored wetland, the ecosystem services provided by Federal Bog would be worth an estimated $257,873, roughly 3% of the assessed parcel value of $7,442,420.

Today, cranberry farms encompass roughly 13,500 acres spread across Southeastern Massachusetts. Cranberry farming is culturally and economically important in the region, but faces ongoing, compounding challenges that make it increasingly difficult for farms to stay profitable, and have led many farmers to consider new options for their farmland. With these different land use scenarios, we invite you to imagine and explore different potential uses of this farming land. In particular, this data tool explores the potential benefits of restoring former cranberry farms to their native wetland state. By using the sliders in the panel on the left, you can visualize different combinations of cranberry farming and restoration distributed across today's actual cranberry farms. These potential land use scenarios were randomly generated by our team.

Figure 6-5: Web application screenshot highlighting Bog-Level Socioeconomic Analysis



Restoration Priority Index

We combined information from our models of ecosystem services to create a ***restoration priority ranking*** that ranges from 0 to 100.

Bogs with a high ranking are predicted to bring particularly high value to the region through water purification, biodiversity protection, and climate resilience. Click on a bog in the map at right to learn more details!

Cranebrook Bog

As a restored wetland, this bog would account for:

- An annual reduction of 10.39 kgs of nitrogen, worth $16,514.
- An annual reduction of 11.26 kgs of phosphorus, worth $1,328.
- A habitat quality score of 0.90, which is 25% above the baseline quality of this bog.
- An estimated 1,515.28 tons of sequestered carbon over 10 years, worth $30,197.

As a restored wetland, the ecosystem services provided by Cranebrook Bog would be worth an estimated $48,039, roughly 2% of the assessed parcel value of $2,503,820.

The restoration priority ranking of this bog is 83 out of a 100, indicating a restoration would have relatively high value in terms of the modelled ecosystem services.

Today, cranberry farms encompass roughly 13,500 acres spread across Southeastern Massachusetts. Cranberry farming is culturally and economically important in the region, but faces ongoing, compounding challenges that make it increasingly difficult for farms to stay profitable, and have led many farmers to consider new options for their farmland. With these different land use scenarios, we invite you to imagine and explore different potential uses of this farming land. In particular, this data tool explores the potential benefits of restoring former cranberry farms to their native wetland state. By using the sliders in the panel on the left, you can visualize different combinations of cranberry farming and restoration distributed across today's actual cranberry farms. These potential land use scenarios were randomly generated by our team.

Figure 6-6: Web application screenshot highlighting Restoration Priority Index

6.3.2 Usability and Potential Utility Study

To gauge the usability and potential utility of this web-based data exploration tool, I developed and conducted a user survey with a subset of the stakeholders I had previously interviewed, who are identified in Table 4.1. The survey was conducted in May 2022. Survey participants were given the url for the web application, and then asked to fill out a Google Form survey sharing their impressions of the site. Survey questions included pre-test questions about participants' experience with web-based technologies and ecosystem services, usability questions intended to produce evaluations of the design and layout, and site utility questions intended to produce evaluations of the potential utility of the site. Given the relatively limited timeframe of graduate school, it was not possible to conduct a longitudinal analysis of how this tool could impact the stakeholder decision-making process; instead, I focused on gathering initial impressions of the usability and potential utility. The full set of questions for the survey can be found in Appendix E.

6.4 Results and Discussion

The reader is encouraged to visit the following web resources to experience the fully-interactive, dynamic nature of the data exploration and visualization tool. As of August 12, 2022, source code, a video walk-through, and the web application itself can be found at the following web locations:

`https://github.com/mitmedialab/CranWebApp`

`https://www.youtube.com/watch?v=o90cTdw8L6k`

`https://cranberry-land-use-explorer.herokuapp.com/`

The survey received seven responses from participants. These participants had a range of occupations, including cranberry farmer, restoration engineer, climate scientist, and city official, among others. Results from the study were generally positive, and expressed interest in the potential of the web tool. Participants liked the layout, design, and functionality of the website. Depending on the individual participant's role and organization, many indicated they would use a tool like this to help their organization achieve its aims. Participants particularly liked the accessibility of the data and analysis, the geospatial approach to ecosystem services, the economic contextualization metrics, and the restoration priority index. The following are representative responses capturing some of this positive feedback:

> "Having available data regarding ecosystem services in a simple, easily accessible format was extremely helpful" - Municipal leader
>
> [We would use it] "frequently as we plan for climate change resiliency" - Cranberry farmer
>
> "The mapping and explicit detailing of ecosystem services included is great" - Scientist
>
> "...I also really like the bog restoration monetary value relative to the assessed value of the property. I think this will help the state and individual municipalities target specific bogs for restoration. I also love the bog restoration priority." - Restoration practitioner

Participants also shared thoughtful critiques about the precision and accuracy of the underlying data and the model results in the web tool, particularly related the nitrogen and phosphorus export models. In particular, there were several comments suggesting that the InVEST models would benefit from more specific data about individual bogs. Some of the representative responses expressing this critique are presented below:

> "I found the water quality advantages for restoration on export nutrients much too broad and question if it's factoring in nutrients retained within the bog (soil, vines, etc.); other factors for possible restoration may include condition of the bog, water levels, etc." - Cranberry businessperson
>
> "I'm puzzled by some of the rankings. A key thing to add (which are not easy to get), would be information about the active bogs." - Scientist

These critiques make sense, and in fact could be expected, because they come from stakeholders with intimate knowledge of specific cranberry bogs in the region, and the InVEST model, as implemented in this dissertation, does not distinguish between cranberry farm bogs based on farm operation data, soil type, or other bog-specific parameters. A follow-up conversation with one of the study participants resulted in new insights about the limitations and possibilities of the InVEST model, and the potential of this data exploration web tool. Reflections on this conversation and these critiques are discussed below. These reflections are focused on the user interface and experience, and build upon some of the critiques of the InVEST model discussed in Section 5.5.1.

6.4.1 Improved Modeling

One of the main conclusions of the study, as it relates to the data presented in the web tool, and the potential utility of the tool, is that there is a need to improve the accuracy of the model estimates in the site. Several participants expressed that the model results did not seem to capture key bog characteristics that could have an important impact on the restoration priority ranking. In particular, a few of the key pieces of information that experts suggested should be included in an evaluation of restoration potential are:

- Bog position in the watershed, which could impact how much pollutant is flowing through the bog
- Sources of nitrogen in the watershed, including the presence or absence of wastewater treatment plants
- Soil type of the bog
- Bog typology, which impacts the hydrology of the site. The three most common bog types in the region are flowthrough, non-flowthrough, and modern or renovated.
- Information on cranberry farm yields

Fortunately, the InVEST modeling platform is quite flexible, and could accommodate these data if available. To do so, one would need to create a more detailed LULC map: instead of grouping all cranberry farms in the same land use class, you could create two different land use classes to distinguish between flowthrough and non-flowthrough cranberry farms, or between bogs with different soil types. One of the major challenges of this approach, however, is the availability of the raw data that could help create those more detailed LULC maps. Factors like bog typology and soil type are not uniformly available across the entire cranberry farming region; they tend to be available only for certain towns or watersheds. This difficulty illustrates the tension between scale and accuracy that is present in many modeling analyses.

6.4.2 Communicating Uncertainty

In light of this tension, it is important to discuss model uncertainty. In Section 5.5.2, I discuss a potential method of computing uncertainty in the actual model estimates. Here, I wish to turn my attention towards communicating model uncertainty to stakeholders in the context of this user-facing web-tool. Assuming that an estimate range were generated using a method as described in Section 5.5.2, it might be possible to indicate the confidence in the model predictions using color or transparency in the geospatial data layers, with higher opacity indicating higher confidence. For metrics, such as the total estimate ecosystem service value, that are reported directly to the user, it would be possible to include a "plus or minus" range next to the reported metric. Another approach to communicating uncertainty in the data inputs would be to make the range of inputs visible and interactive to site users. For example, there is a wide range of possible values for the social cost of carbon. It could be instructive to allow users to manually adjust the value of this parameter, perhaps through a slider interface, and witness in real-time how different carbon pricing impacts the potential financial value of restoration.

6.4.3 Bog Selection

One recurring critique of the data exploration tool was the use of randomly-generated LULC scenarios to frame and drive the analysis. Several survey participants commented that they didn't understand why the analysis was framed through random groupings of bogs, and that they would have preferred to be able to select individual bogs, or specific groupings of bogs, for the analysis. Unfortunately, this limitation in user experience was driven by computational constraints: due to the long run-time and computational complexity of the InVEST models, it was not possible to run them "on-the-fly" or in the browser. For example, the Habitat Quality model could take up to 15 minutes to run a single iteration of the model. Given my personal computing equipment, using predetermined land use scenarios was a necessary simplification in order for me to be able to run the InVEST model.

However, there are several approaches that might make it possible for users to dynamically select individual bogs and perform "on-the-fly" ecosystem service evaluation. With the advent of cloud-based, high performance computing, there are now readily-accessible, commercially available solutions for performing complex calculations, such as Amazon Web Services or Google Cloud Computing. One approach to enabling a more dynamic experience for users would be to run the InVEST model "on-the-fly" using a high performance cloud computing server in the background of the web application. Another option would be to use one of these services to run every combination of restoration through the InVEST model in advance of presenting the analysis to users. The pre-calculated estimates could be stored in the site, and dynamically presented to users based on their cranberry bog selections. Both these options would harness the power of high performance computing and big data storage. Though considering the scalability and computational complexity of the InVEST model was outside the scope of my dissertation work, it is important to note the positive impact these technologies could have on user experience.

Despite the critiques and limitations uncovered through the user survey, it is clear the development of this web application is an important starting point for allowing stakeholders to interact with and become familiar with the potential benefits of ecosystem services from wetland restorations. This dissertation represents a first attempt at the modeling work, and uncovers ample opportunities to improve the InVEST models and the user experience. The InVEST models can accept a wide range of data; with thoughtful customization and refinement of inputs, particularly by including more detail in the LULC layer, the models could be leveraged to provide more precise estimates. The goal of this analysis, presented in the novel interface of this web application, is to unlock a new way of approaching restoration in the region and to build knowledge around the potential value of ecosystem services.

Chapter 7

Conclusion

7.1 Contributions

This is an interdisciplinary dissertation with a particular focus on performing analysis to inform real-life decisions. Thus, this dissertation contributes both academic and practical knowledge in several different fields. In particular, the key contributions of this research are as follows:

7.1.1 Subject-matter Contributions

Contextual Analysis of the MA Cranberry Industry

I used the *Systems Architecture Framework* (SAF) to conduct a systematic analysis of the MA cranberry industry to identify important system contextual factors and key stakeholders, and understand the needs and objectives of these stakeholders. Data was collected through stakeholder interviews and a literature review, and analyzed by systematically stepping through the SAF. The contributions of this work include a stakeholder mapping and an analysis of the key needs and objectives of system stakeholders. The SAF process was used to identify and evaluate a system form – an ecosystem service analysis and valuation presented in a web-based data exploration tool – that would support the needs and objectives of several different stakeholders.

Environmental and Economic Analysis of Land Use Scenarios

I conducted a regional-scale, spatially-explicit environmental and economic analysis of different land use scenarios through the lens of water quality, habitat quality, and carbon sequestration. This research utilized the EVDT framework to structure and design my analysis, and InVEST ecosystem service models to model individual ecosystem services under different land use scenarios. The contributions of this work include spatially explicit maps of the estimated distribution of ecosystem services under different land use scenarios, and maps of the estimated value these ecosystem services would represent over a 10-year period. Additionally, this research contributes economic analysis to contextualize the value of the ecosystem services in the region, and presents a method for prioritizing the wetland restoration of individual cranberry bogs.

Web-Based Data and Scenario Exploration Tool

To communicate the results of the ecosystem service modeling and analysis, I developed a user-friendly web-tool that addresses the information needs of primary stakeholders and builds knowledge around the value of ecosystem services. I then conducted a user study with key industry stakeholders to gauge the usability and potential utility of the web-based tool. The contributions of this work include the development of a flexible and accessible, user-facing web application for the ecosystem service analysis, as well as reflections on the strengths and weaknesses of the web-based data exploration tool that point towards a future research agenda for this work.

7.1.2 Methodological Contributions

Evaluation of InVEST Ecosystem Service Models

In the course of using the InVEST ecosystem service models, I was able to evaluate the suitability of using the InVEST ecosystem service models in the context of Southeastern MA, as well as reflect more broadly on the benefits and challenges of the InVEST modeling platform. InVEST was an appropriate starting point for this project because it is well-supported and well-documented, can be used anywhere in the world, and is accessible to non-experts. Some of these benefits, however, came at the cost of the central limitation of the modeling platform: the highly simplified nature of the model leads to significant uncertainty in the modeling outputs. In this dissertation, I present a discussion of these trade-offs and suggestions for overcoming this limitation of InVEST.

Contributions to the EVDT Framework Literature and Modeling Library

EVDT is an integrated modeling framework that was developed in the Space Enabled Group at the Media Lab. It is specifically designed to address the feedback loops and interactions of complex systems in order to guide sustainable development. EVDT has been implemented in a number of diverse case studies, which together demonstrate the viability of using the EVDT framework to address sustainable development challenges across a variety of regions and application spaces. This dissertation, which at the time of writing, is the first completed doctoral dissertation to implement the EVDT framework, contributes to the EVDT literature and supports the argument that the EVDT framework is appropriate and well-suited for addressing the challenges of complex systems and sustainable development.

The EVDT framework operates by uniting four submodels – the Environment, Vulnerability, Decision, and Technology models – in an integrated framework. These models can be drawn from earth science, social science, and complex systems, among other fields. This dissertation contributes to a growing library of submodels by demonstrating and documenting how different submodels can be incorporated into the EVDT framework, and reflecting on the challenges and opportunities of using these particular submodels.

7.2 Opportunities for Future Inquiry

This thesis took an extraordinarily broad, interdisciplinary approach to the challenge of land use decisions in Southeastern MA. It was important to me to complete an end-to-end project starting with efforts to understand context in a systematic way using the Systems Architecture Framework, and ultimately closing the loop by building a tool for stakeholders and evaluating their impressions of it. As a consequence, however, there remain many areas of this dissertation that would benefit from deeper inquiry. One of the high-level contributions of this thesis was creating a system that links modeling and data with interviews and usability work; at times, in the pursuit of this system, I had to sacrifice depth for breadth. Thus, I will close with a discussion of areas of inquiry that seem like natural next steps given the work completed in this dissertation.

7.2.1 Improve Model Accuracy with Scientific and Operational Data

First, I would focus on improving the accuracy of existing models with the inclusion of more specific bog-level data. Based on conversations with scientific experts, I believe specific data that could improve these models includes: whether or not bogs are flow-through, non-flowthrough, or modern bogs; bogs' position in the watershed; bog soil type; and farming activities. These data could be incorporated into InVEST models by creating multiple LULC classes for cranberry bogs that reflect these more fine-grained distinctions.

Similarly, there is a need for ongoing wetland restoration science, particularly as it pertains to cranberry bogs, and further incorporation of this science into these ecosystem service models. For several of the ecosystem service models implemented, it was difficult to calibrate the model because there is still so much uncertainty about the impact of restoration on ecosystem services in the cranberry bog setting. The study of wetland restoration on cranberry bogs is relatively young, with new insights and science being developed every year. Further integration of this science will help fine-tune estimates and lead to more accurate modeling tools.

7.2.2 Analyze Additional Ecosystem Services and Socioeconomic Factors

Another area of rich opportunity is the development and incorporation of models for additional ecosystem services. Ecosystem services that would be particularly interesting to include in this model include flood mitigation, discussed below, and recreation. Beyond additional ecosystem services, there is an opportunity to incorporate other regional economic and social factors that impact land use. My original thesis plan proposed several additional factors which ended up falling outside the scope of this work. These included economic factors (e.g. jobs and revenue from the cranberry industry and associated events) and sociocultural factors (e.g. festivals, identify, agrotourism). Driven by my SAF analysis, I ended up focusing on the most important environmental factors in the region, but the understanding of land use decisions could be made even more robust by incorporating additional factors.

Discussion of Flood Mitigation

I had originally planned to evaluate the impact of restoration relative to cranberry farming in the context of flood resilience. Flood mitigation is frequently cited as a benefit of wetland restoration, both in the context of MA cranberry bog restoration, and in coastal resilience studies more broadly (K. Ballantine et al., 2020; Russi D. ten Brink P. & N., 2013). Ultimately, due to time constraints and increased complexity in other parts of this work, I was not able to complete this analysis. However, I share my updates and observations here in hopes that they may be useful to researchers in the future.

I considered, evaluated, and tested three InVEST models to perform this analysis: the Coastal Vulnerability model, the Seasonal Water Yield Model, and the Urban Flood Risk Mitigation Model. The Coastal Vulnerability model "produces a qualitative estimate of...exposure in terms of a vulnerability index, which differentiates areas with relatively high or low exposure to erosion and inundation during storms" (Sharp et al., 2020). I decided not to use this model because of its explicit focus on coastal areas; because many of the cranberry bogs in Southeastern MA are further inland, I hypothesized that bog restoration would not have a major impact on this model's coastal vulnerability index given the time and spatial scales considered in this study. Additionally, a practical consideration was that the data format produced by this model – a series of points along the coastline indicating coastal risk – was incompatible with the spatially explicit raster maps produced by other models.

The other models I considered were the Seasonal Water Yield model, which "estimat[es] the effect of landscape management on the water supply service", and the Urban Flood Risk Mitigation model, which calculates the reduction in stormwater runoff due to natural infrastructure during storm events (Sharp et al., 2020). While the Seasonal Water Yield does not take into account major storm events, it does distinguish between seasonal "quickflow" and "baseflow" water flows, with quickflow indicating water runoff that occurs within hours and days of a precipitation event, and baseflow infiltrating the soil and staying in the watershed for months to years. My approach with the Seasonal Water Yield would have been to examine the change in quickflow runoff between different land use scenarios. With the Urban Flood Risk Mitigation model, my approach would have been to examine stormwater runoff under different land use scenarios in the aftermath of hypothetical extreme weather events.

After some initial work on these models, there remained open questions which will be important for future researchers to consider. The first is whether flooding risk in the region is primarily due to stormwater from precipitation events, or from ocean storm surge due to sea level rise. Though the absorption of stormwater runoff is frequently mentioned as a potential benefit of wetland restoration, it was also communicated to me in an interview that, due to the region's flat topography and permeable soils, flooding from rainstorms has typically not been severe, and that flooding from ocean surge is a greater concern (A. Hackman, personal communication, August 9, 2021). On the other hand, under a changing climate, this risk calculus may change. For example, during Hurricane Ida in September 2021, Plymouth, MA received nearly 8 inches of rain in 12 hours, which resulted in flooding, damage, and power outages (CBS Boston, 2021).

Another open question that I believe requires further research is how much a wetland restoration would specifically improve water retention capacity. In particular, the Seasonal Water Yield and Urban Flood Risk Mitigation models rely on specifying the *curve number* for each land type, which is a hydrologic parameter used to predict runoff or infiltration. An initial review of the literature did not yield a published *curve number* for either cranberry bogs or restored wetlands. However, I did find a source suggesting that cultivated cropland and wetlands had identical *curve numbers* (Ahmad, Durrans, Dietrich, & Haestad Methods, 2003). If I had used these numbers, I do not expect the model would have predicted any difference in runoff retention between the cranberry bog and restoration scenarios. Further investigation of the runoff reduction potential of restored wetlands will be necessary before using a model to accurately predict the improved flood mitigation potential of bog restorations in the region.

7.2.3 Improve Ecosystem Service Valuation

Another avenue of future work would be to improve and expand upon the ecosystem service valuation process; in other words, refine and expand the methods that were used to estimate the economic value of wetland restorations. Due to the general nature of the output of the

Habitat Quality model, a value estimation was not performed for that model, likely leading to an underestimation of ecosystem services in my analysis. Ecosystem service valuation is an active area of research, so there are ample opportunities to apply and refine different valuation methods. For example, Griffin et al. (2020) use a "willingness-to-pay" approach to estimate the value of "recreational and nonuse values as a function of water quality". Expanding the number of ecosystem services addressed in this work, and applying cutting edge valuation methods to these models will likely lead to estimates of ecosystem service value that more accurately represent the potential benefits of restoration.

7.2.4 Further Evaluate Data Exploration Tool

Further refinement and evaluation of the web-based data exploration tool is another important part of a future research agenda. A long-term research goal for this work would be to understand the impacts and utility of the web-based tool as it relates to stakeholder decision-making. Given the time frame of this thesis, I was only able to gather initial impressions about the usability and potential utility of the tool. Ideally, the utility of the tool could be established through longitudinal studies, expanded user feedback, workshops, and other standard user experience research methods. These activities would also provide the opportunity to refine the functionality of the site itself, and address some of the user interface issues discussed in Section 6.4.

7.2.5 Incorporation of Alternative Ecosystem Service Models

Incorporating alternative, non-InVEST ecosystem service models is another way to refine the analysis presented in this dissertation. InVEST's relative simplicity and its ability to model multiple ecosystem services using the same modeling platform made InVEST a convenient, accessible, and appropriate modeling approach given the relatively broad scope of this project. When combining the outputs and results from different analyses, simple and intuitive models help reduce overall complexity and ensure successful integration.

However, after using InVEST for the first version of this analysis, it is clear that there is an opportunity to refine the analysis using more complex, specific models. Ecosystem service modeling is a field with remarkable depth and complexity, with a profusion of models that aim to represent single ecosystem services in great detail. Whereas InVEST is explicitly focused on geospatial data, other ecosystem service models may produce results in a tabular format. Sometimes these models are specific to a particular ecosystem, terrain, or region. For example, DNDC (DeNitrification-DeComposition) is a process-based model specifically designed to model carbon and nitrogen biogeochemistry in agricultural soil ecosystems (Zhang, Li, Trettin, Li, & Sun, 2002). Other examples are the Massachusetts Estuaries Project's Linked Watershed-Embayment Model and the Waquoit Bay Nitrogen Loading Model, which are two widely used models for estimating watershed nitrogen levels (Howes, Ramsey, & Kelley, 2001; Valiela et al., 1997; Valiela, Geist, Mcclelland, & Tomasky, 2000; Kennedy & Hoekstra, 2021). The increased complexity of these models could mean they take longer to calibrate and run, or require more specialized knowledge on the part of the researcher.

The analysis and web-based data tool presented in this dissertation are relatively modular. All the InVEST modeling work is conducted offline, then uploaded to the web-based data tool. This structure would make it relatively simple to swap in the results or analysis from a different ecosystem service model: one could simply run the alternative model, then upload the results to the appropriate data layer in the web application tool. If the output format of the alternative model were not geospatial, results could still be aggregated by cranberry bog and presented in a geospatial format using the Mapbox interface. When approached in a strategic, thoughtful way, incorporating alternative, non-InVEST ecosystem service models could improve the precision of the estimates presented in the web tool, and should be considered as part of the future research agenda for this work.

7.2.6 Analyze Other Land Use Options

This dissertation focuses on two potential land use outcomes for cranberry farmers: continued cranberry farming, or an active wetland restoration. However, there are a number of other options available to farmers, including: undergoing farm renovations to improve efficiency, planting newer and more robust cranberry varietals, diversifying their income streams via solar panel installation or alternative crops, selling their land to developers, or simply abandoning the land (Massachusetts Department of Agricultural Resources, 2016).

While I had initially proposed to evaluate and model several of the options available to farmers, in the course of refining my research plan, I chose to focus just on farming and restoration because they were the most relevant to the stakeholders I was in conversation with, and because I could draw support and data from my research group and Living Observatory's ongoing research on wetland restoration. Narrowing the scope of research is a normal part of applying the EVDT framework and was a conscious choice.

However, to offer more comprehensive support to stakeholders, it will ultimately be important to address the wider range of land use options in the model and web tool. One of the more prominent alternate land use options is real estate development. If a land owner or municipality was using this web-based data tool to explore options for a cranberry farm, it would be useful for them to be able to compare the potential value of ecosystem services to the potential profit from selling the land to a developer.

To hint at this comparison, in this dissertation, I computed a metric that compared the potential value from ecosystem services to the assessed parcel value, which I was able to pull from tax records. This computed metric had a very wide range: in some cases, the potential value from ecosystem services was very large compared to the assessed parcel value, and in other cases, it was relatively small. This was a coarse comparison metric, but would likely yield additional insights upon further study.

To compute a more accurate estimation of real estate value for cranberry farms, one could imagine a real estate valuation model that fused farm location, population center proximity, the percentage of wetland area, and the amount of road frontage, among other factors. Being able to compare the potential real estate sale price to the potential value from ecosystem services could be useful for an individual landowner, or for a decision-maker at the town or state level. One potential outcome of this comparison, which would extend the hypothesis of this dissertation, would be to demonstrate to these stakeholders that a wetland restoration, in lieu of or compared to real estate development, could offer significant financial value.

While this proposed real estate assessment model would capture the potential economic value of selling land to a real estate developer, it would not capture the environmental impacts. A critical element of the driving theory behind this dissertation is that environmental harms must be identified and penalized, while environmental benefits should be recognized and rewarded. Thus, when evaluating real estate development, or other potential future uses of land, it would be important to model the environmental impacts, which could be done using InVEST.

To leverage the InVEST platform for this analysis would require information on how these different land uses impact the different environmental factors discussed in this dissertation: nitrogen and phosphorus loading, carbon storage, and threats to biodiversity and habitat quality. For example, LO researchers are currently investigating how restoration impacts GHG emissions in restored wetlands; applying the InVEST model to a real estate development project would require information on how that new construction affected the GHG balance of the land. Though building out representations of these alternative land use options would incur significant time and complexity, doing so would likely improve the long-term utility of the data exploration tool.

7.2.7 Applications Beyond the MA Cranberry Industry

One recurring question I received during the course of this dissertation project was on the possibility of extending the approach presented in this dissertation to regions or cases beyond the cranberry industry in Southeastern MA. In short, the concepts, frameworks, and technologies used in this dissertation are extremely portable. The idea that we can align environmental and economic objectives by considering the value of ecosystem services is universal, and is, in fact, receiving increased attention in light of growing awareness of the climate and biodiversity crises. This type of approach would be naturally applicable in deciding where to build homes, grow crops, or preserve forests. In terms of frameworks and technologies, the EVDT framework is quite flexible, and has been applied in a number of different geographical locations and case studies (J. B. Reid & Wood, 2020a). As a modeling platform, InVEST is flexible and location-agnostic, and is designed to be applied to any region of the world. Mapbox, too, is completely location-agnostic and offers many opportunities to customize the presentation of geospatial data.

The main challenge in extending this research to other regions, however, would be the difficulty of retrieving the region-specific data to calibrate the models to different regions. Though InVEST can be run for any region in the world, the researcher needs to supply local geospatial data and calibration parameters, which can be a time-consuming process. Thus, in the context of land use decisions in other regions, the work presented in this dissertation should be thought of as a blueprint, not a turnkey platform.

7.3 Aligning Environmental and Economic Objectives in Land-Use Decision-Making

This dissertation presents a stakeholder-informed, data-driven analysis of land use decisions in the MA cranberry industry. The goal of the research was to advance an economic argument for wetland restoration in the region, and build accessible tools for stakeholders that support sustainable decision-making. To address these goals, I undertook three main research efforts. First, using methods from systems engineering and social science, I used the Systems Architecture Framework to conduct a contextual analysis of the industry via stakeholder interviews and a literature review. Second, I leveraged the EVDT integrated modeling framework and the InVEST ecosystem service modeling platform to investigate the environmental and economic impacts of different land-use scenarios. Finally, I developed and evaluated a web-based data exploration tool that allows stakeholders to explore the impacts of restoration and provides geospatial insights into key land use scenarios.

With such a broad scope and interdisciplinary approach, this research did encounter some challenges related to data availability, model accuracy and calibration, and computation complexity. Working with the InVEST models provided the opportunity to reflect on some of the advantages and limitations of the modeling platform, while conducting a user study to evaluate the data explorer web tool generated insights on users' decision-making needs.

Addressing gaps in several bodies of literature, including the study of cranberry bog restoration in MA and the development of the EVDT framework, this dissertation lays the groundwork for regional-scale analysis of the ecosystem services associated with cranberry bog wetland restorations, and delivers tools that are scientifically-informed, dynamic, and driven by the needs of primary stakeholders. The intent of this research was to bridge the gap between scientists, land-owners, practitioners, and municipal leaders, advancing the approach of ecosystem service valuation as a means of discovering synergies between environmental and economic objectives, and making a compelling and novel economic argument for wetland restoration in the region.

Appendix A

Living Observatory Goals

- Develop a distributed biological research station for the purpose of long-term monitoring, interpreting, and learning about how ecosystem function develops following ecological wetland restoration of retired cranberry farms.
- Develop metrics and methods that can be used to monitor, select and evaluate the success of ecological restoration projects.
- Build an interdisciplinary learning community of technologists, scientists, artists, educators, students, restoration experts and policy makers in order to develop projects that measure long-term change in function and to create experiences that invite the public to witness these changes.
- Contribute to social, economic and scientific understanding of ecological restoration and human lifestyle choices, including the decisions by landowners as they take agricultural wetlands out of production.

Appendix B

Questions for Stakeholder Interviews

The following questions were used, where applicable, to loosely structure stakeholder interviews conducted between late 2020 and Spring 2022:

- What is your background and how did you become involved in the MA cranberry industry?
- What organization are you associated with and what is your personal or professional role in that organization?
- What are the key goals of your work or your organization?
- How does your organization currently accomplish these goals?
- What types of data or tools does your organization use to accomplish these goals? Do you track any specific metrics or data?
- What are the key challenges you or your organization faces?
- What organizations or stakeholders do you and your organization regularly interact or collaborate with?
- Which local, state, or federal policies impact your work?
- How does cranberry bog restoration fit into the context of your organization's work?
- What are the main barriers to wetland restoration of cranberry bogs in the region?

Appendix C

Cranberry Industry Literature Review

As part of the research detailed in Chapter 4, I conducted a literature review that involved compiling and analyzing government and industry reports, historical accounts, and published academic research on cranberry farming and cranberry bog restoration. To compile publications and reports, I searched for the terms *"cranberry farming "*, *"cranberry farming Massachusetts"*, and *"cranberry farming economics"* on the following websites:

- Google Scholar
- Massachusetts state website (`https://www.mass.gov/`)
- United States Department of Agriculture (USDA) website (`https://www.usda.gov/`)
- National Agricultural Statistics Service website (`https://www.nass.usda.gov/`)
- LO website (`https://www.livingobservatory.org/publications`)
- USDA Agricultural Research Service website
- UMass Cranberry Station website (`https://ag.umass.edu/cranberry/research-extension`)

Reports and literature were selected based on their relevance to the research questions presented in this dissertation, specifically, the environmental, economic, and sociocultural impacts of cranberry farming and wetland restoration of cranberry bogs in MA. The full list of reviewed literature, organized by category and arranged chronologically, with a brief description, can be found below.

C.1 Government, Industry, and Historic Reports

These sources detail the history of cranberry cultivation in MA, the economic impacts of cranberry production on the state, and the government programs directed towards cranberry growers and the cranberry industry.

- Mason (1926): Historic overview of the cranberry industry
- Randall (2010): Brief article on MA cranberry bog redesign
- Cox and Walker (2012): History of cranberry culture and consumption in MA
- Farm Credit East (2015): MA Cranberry Cost of Production study
- Massachusetts Department of Agricultural Resources (2016): MA Cranberry Revitalization Task Force Report
- USDA National Agricultural Statistics Service (NASS) (2020): US cranberry production highlights

C.2 Academic Publications on Cranberry Farming

These publications contain information and research on the best management practices for cranberry farming, and environmental impacts of cranberry farming. Many publications in this category came from, first, a branch of the USDA's Agricultural Research Service that focuses on the environmental impacts of cranberry farming, and second, the UMass Amherst Cranberry Station, which is an outreach and research center dedicated to maintaining and enhancing supporting the MA cranberry industry.

- Howes and Teal (1995) : Nutrient balance of MA cranberry bogs
- Caruso (1996): Trends in cranberry production

- Davenport (1996): Effect of nitrogen fertilizer on cranberry yield
- C. J. DeMoranville (2006): Best management practices for cranberry farming in MA
- Blake et al. (2007): Cranberry grower perceptions of integrated pest management
- H. Sandler and DeMoranville (2008) : MA Cranberry production guide
- H. A. Sandler (2008): Challenges in integrated pest management for MA cranberry production
- Gordon (2009): Report on costs of renovating MA cranberry farms
- H. A. Sandler et al. (2012): Increasing sustainability of MA cranberry production
- Alston et al. (2014) : Economic impact of the North American cranberry industry
- Ellwood et al. (2014) : Cranberry flowering times and climate change in southern MA
- C. DeMoranville (2015) : MA Cranberry nutrient management guide
- Caron et al. (2017): Guidelines for optimizing water use in cranberry production
- Gumiere et al. (2017): Precision agriculture for cranberry production
- Kennedy (2015): Impacts on groundwater due to cranberry farm flooding
- Kennedy et al. (2017): Managing phosphorus loss from cranberry farms
- Kennedy, Alverson, et al. (2018) : Seasonal dynamics of water and nutrients in agricultural peatland
- Kennedy, Wilderotter, et al. (2018) : Geospatial model of peat thickness in cranberry bogs
- Hoekstra et al. (2019) : Opportunities for riparian wetland restoration
- Kennedy (2019) : Phosphorus loss during cranberry harvest
- H. A. Sandler et al. (2019): Expectations for cranberry growth with solar panels

- Gareau et al. (2020): MA cranberry grower social networks
- Kennedy et al. (2020) : Nitrogen and phosphorus export from agricultural peatlands
- Kennedy and Hoekstra (2021) : Measuring and modeling nitrogen export from cranberry farms

C.3 Academic Publications on Wetland Restoration of Cranberry Farms

These publications include information on the MA DER restoration program, and the impacts of wetland restoration on water quality, GHG fluxes, and biodiversity, among other factors. Many of these publications came out of the LO research portfolio.

- Russell et al. (2016) : Study on auditory augmented reality device in Tidmarsh setting
- K. A. Ballantine et al. (2017) : Denitrification in agricultural wetlands
- Burns (2017) : Cranberry farm assessment for wetland restoration potential
- Haddad et al. (2017) : Virtual reality environments from wetland restoration sensing
- Neill et al. (2017) : N and P balances of cranberry bogs
- B. Mayton et al. (2017) : Environmental sensor network and applications
- Gareau et al. (2018) : Sociological study of New England cranberry farmers
- MA DER (2018) : Brief overview of MA DER cranberry bog restoration program
- Norriss (2018) : GIS data analysis of cranberry bog siting
- Christen et al. (2019) : Assessment of faunal diversity in restored wetlands
- Duhart et al. (2019): Using deep learning for acoustic wildlife monitoring
- Harvey et al. (2019) : Evaluation of stream and wetland restoration

- Andras et al. (2020): Effect of restoration on prokaryotic communities in peatland soils
- K. Ballantine et al. (2020) : LO Preliminary Benefits Assessment
- Bartolucci et al. (2020) : Study of GHG fluxes in retired and restored cranberry bogs
- Klionsky et al. (2020): Analysis of plant species richness on restored wetlands
- Rubin et al. (2021): Wetland microbial communities after restoration of cranberry farm

Appendix D

InVEST Data Sources

One strength of the InVEST ecosystem service modeling platform is that it is location-agnostic; that is, it can be used for any region in the world. To do so, however, the user must supply region-specific geospatial data and calibration parameters. This appendix details the data and data sources used for running three InVEST ecosystem service models for the research described in this dissertation.

D.1 Geospatial Data Sources

Table D.1 presents the geospatial data used for the three different InVEST ecosystem service models, indicates for which of the three models the data was utilized, and cites the source of the data. In the table, "NDR" is used to refer to the Water Purification InVEST model, "HQ" is used to refer to the Habitat Quality InVEST model, and "CSS" is used to refer to the Carbon Storage and Sequestration InVEST model.

D.2 NDR Model Biophysical Table

The *biophysical table* for the NDR model contains information on nutrient loading rates and nutrient retention by LULC type. It is a key input to the NDR model, and was developed via a literature search to discover region-specific values for different land use types, where available.

For each LULC type, the biophysical table requires a *load_n* and a *load_p* value, which stand

Data Set Name	InVEST Model(s)	Data Source	Notes
Land use land cover (LULC)	NDR, HQ, CSS	USGS (2019)	Modified LULC map to include cranberry farms as discussed in Section 5.3.2
Digital elevation model (DEM)	NDR	USGS (2018)	Merged together DEM tiles for Southeastern MA region
Annual precipitation map	NDR	National Weather Service (2020)	Imported and georeferenced JPG precipitation image in QGIS
Watersheds map	NDR	MassGIS (2005)	Used HUC-12 sub-basins; used subset for calibration, and sub-basins with 5 or more cranberry bogs for NDR model run
Agriculture threat map	HQ	USGS (2019)	Modified LULC map in QGIS to isolate agricultural land uses; modified threat map to reflect hypothetical changing land use scenarios
Development threat map	HQ	USGS (2019)	Modified LULC map in QGIS to isolate development land uses
Roads threat map	HQ	MassGIS (n.d.)	Used road levels 1-4 for "Roads1" threat layer, and levels 5-6 for "Roads2" threat layer

Table D.1: Geospatial Data used for InVEST modeling

for *nitrogen load* and *phosphorus load*. These values, given in $\frac{kg}{ha*year}$, represent the nutrient loading for each land use class; essentially, the average amount of nitrogen or phosphorus that would be expected to come from a given area of a particular LULC type. Nitrogen and phosphorus are generated through certain biogeochemical processes, or can come from synthetic sources such as fertilizers or pesticides.

For each LULC type, the biophysical table also requires *eff_n* and *eff_p* values, which indicate the "nutrient retention efficiency" of that particular land type, given as a unitless value between 0 and 1. This value is "the maximum proportion of the nutrient that is retained on this LULC class" (Sharp et al., 2020). In general, natural vegetation land use types, such as forests or wetlands, have have retention efficiency, while developed land use types, such as industrial or high-density residential areas, have low retention efficiency.

Finally, the biophysical table also requires a *critical length* for each LULC class-nutrient pair, which is "the distance after which it is assumed that this LULC type retains the nutrient at its maximum capacity" (Sharp et al., 2020). Values for critical length were not derived from the literature; instead, they were calibrated according to the process described in Section 5.3.4. The critical length selected for nitrogen modeling was 300, and the critical length selected for phosphorus modeling was 270.

Tables D.2 and D.3 present the biophysical tables, for nitrogen and phosphorus, respectively, used for the NDR model estimates presented in this dissertation, alongside the data sources for each value in the table. Because critical length values were uniform across all LULC types, by nutrient, and because they were not derived from the literature, they are not presented in the table.

D.3 Habitat Quality Model

The Habitat Quality model requires a user-defined *threats table* and *sensitivity table*. The threats table indicates the distance over which threats in the region can impact or harm biodiverse habitats, while the sensitivity table indicates the suitability of each LULC class as a habitat for biodiversity, on a scale of 0 to 1, and for each threat-LULC type pair, how sensitive that LULC type is to that threat. The threat and sensitivity tables were developed by adopting standard values given in the Willamette example drawn from InVEST user guide, and then calibrating these parameters to the Southeastern MA region using the process described in Section 5.3.5 (Sharp et al., 2020). Based on the calibration, the "threat distances" are 25% higher than the standard values, the "threat weights" are 25% higher than the standard values, and the "sensitivity to threats" values are 25% lower than the standard values. These calibrations are reflected in the threat and sensitivity tables, which are presented in Tables D.4 and D.5.

D.4 Carbon Storage and Sequestration

The Carbon Storage and Sequestration model requires a user-defined *carbon pools table*, which contains information on the average amount of carbon, in $\frac{tons}{ha}$, for each LULC type. Though the model allows these carbon pools to be split among four different carbon pools (above-

LULC Type	LULC Code	load_n	load_n source	eff_n	eff_n source
Open water	11	2.2	Withers and Jarvie (2008)	0.1	Saunders and Kalff (2001)
Developed, open space	21	25.57	White et al. (2015)	0.3	Groffman et al. (2004)
Developed, low intensity	22	29.63	White et al. (2015)	0.2	Groffman et al. (2004)
Developed, medium intensity	23	29.63	White et al. (2015)	0.2	Groffman et al. (2004)
Developed, high intensity	24	47.5	White et al. (2015)	0.08	Groffman et al. (2004)
Barren land (rock/ sand/ clay)	31	3.7	Edwards and Miller (2001)	0.3	Lucas and Greenway (2011)
Deciduous Forest	41	8.07	White et al. (2015)	0.7	Weitzman and Kaye (2016)
Evergreen Forest	42	8.07	White et al. (2015)	0.7	Weitzman and Kaye (2016)
Mixed Forest	43	8.07	White et al. (2015)	0.7	Weitzman and Kaye (2016)
Shrub/ Scrub	52	9.93	White et al. (2015)	0.6	Sharp et al. (2020)
Grassland/ Herbaceous	71	12.0	White et al. (2015)	0.54	Sharp et al. (2020)
Pasture/ Hay	81	9.44	Reckhow, K.H., Beaulac, M.N., Simpson (1980)	0.45	Sharp et al. (2020)
Cultivated Crops	82	11.88	White et al. (2015)	0.15	Pärn et al. (2012)
Restored wetland	85	3.9	Used herbaceous wetland value	0.65	Valiela et al. (1997)
Woody wetlands	90	7.3	Edwards and Miller (2001)	0.65	Valiela et al. (1997)
Emergent Herbaceous Wetlands	95	3.9	Edwards and Miller (2001)	0.65	Valiela et al. (1997)
Cranberry Bogs	99	14.0	Kennedy et al. (2020)	0.58	Kennedy and Hoekstra (2021)

Table D.2: Biophysical Table used for NDR Modeling - Nitrogen

LULC Type	LULC Code	load_p	load_p source	eff_p	eff_p source
Open water	11	0.10	Withers and Jarvie (2008)	0.69	Reddy et al. (1999)
Developed, open space	21	3.55	White et al. (2015)	0.24	Hobbie et al. (2017)
Developed, low intensity	22	3.55	White et al. (2015)	0.24	Hobbie et al. (2017)
Developed, medium intensity	23	1.84	White et al. (2015)	0.24	Hobbie et al. (2017)
Developed, high intensity	24	0.54	White et al. (2015)	0.24	Hobbie et al. (2017)
Barren land (rock/ sand/ clay)	31	0.18	Edwards and Miller (2001)	0.24	Hobbie et al. (2017)
Deciduous Forest	41	0.13	White et al. (2015)	0.7	Sharp et al. (2020)
Evergreen Forest	42	0.13	White et al. (2015)	0.7	Sharp et al. (2020)
Mixed Forest	43	0.13	White et al. (2015)	0.7	Sharp et al. (2020)
Shrub/ Scrub	52	0.71	White et al. (2015)	0.6	Sharp et al. (2020)
Grassland/ Herbaceous	71	1.77	White et al. (2015)	0.7	Sharp et al. (2020)
Pasture/ Hay	81	4.05	Reckhow, K.H., Beaulac, M.N., Simpson (1980)	0.8	Sharp et al. (2020)
Cultivated Crops	82	0.53	White et al. (2015)	0.15	White et al. (2015)
Restored wetland	85	0.34	Land et al. (2016)	0.46	Land et al. (2016)
Woody wetlands	90	0.25	Edwards and Miller (2001)	0.38	Kovacic et al. (2000)
Emergent Herbaceous Wetlands	95	0.25	Edwards and Miller (2001)	0.35	Kovacic et al. (2000)
Cranberry Bogs	99	3.04	Kennedy et al. (2020)	0.69	Kennedy, Alverson, et al. (2018)

Table D.3: Biophysical Table used for NDR Modeling - Phosphorus

Threat Name	Threat Max Distance	Threat Weight	Threat Decay
Agriculture	10.0	0.875	linear
Development	12.5	1.0	exponential
Roads1	3.75	1.0	linear
Roads2	1.25	0.875	linear

Table D.4: Threats Table for Habitat Quality Model

LULC Type	LULC Code	Habitat Suitability	Agriculture	Development	Roads1	Roads2
Open water	11	1.0	0.53	0.67	0.53	0.41
Developed, open space	21	1.0	0.3	0.34	0.3	0.19
Developed, low intensity	22	1.0	0.23	0.38	0.23	0.11
Developed, medium intensity	23	0.0	0.0	0.0	0.0	0.0
Developed, high intensity	24	0.0	0.0	0.0	0.0	0.0
Barren land (rock/ sand/ clay)	31	0.0	0.0	0.0	0.0	0.0
Deciduous Forest	41	1.0	0.45	0.60	0.45	0.34
Evergreen Forest	42	1.0	0.38	0.52	0.38	0.26
Mixed Forest	43	1.0	0.45	0.60	0.45	0.38
Shrub/ Scrub	52	1.0	0.3	0.45	0.3	0.19
Grassland/ Herbaceous	71	1.0	0.3	0.45	0.3	0.19
Pasture/ Hay	81	1.0	0.23	0.38	0.23	0.11
Cultivated Crops	82	0.5	0.23	0.38	0.23	0.11
Restored wetland	85	1.0	0.53	0.67	0.53	0.58
Woody wetlands	90	1.0	0.53	0.67	0.53	0.58
Emergent Herbaceous Wetlands	95	1.0	0.53	0.67	0.53	0.58
Cranberry Bogs	99	0.75	0.23	0.38	0.23	0.11

Table D.5: Sensitivity Table for Habitat Quality Model

LULC Type	LULC Code	Total Carbon	Source
Open water	11	0	Sharp et al. (2020)
Developed, open space	21	80	Sharp et al. (2020)
Developed, low intensity	22	51	Sharp et al. (2020)
Developed, medium intensity	23	23	Sharp et al. (2020)
Developed, high intensity	24	0	Sharp et al. (2020)
Barren land (rock/ sand/ clay)	31	0	Sharp et al. (2020)
Deciduous Forest	41	179	Smith et al. (2013)
Evergreen Forest	42	210	Smith et al. (2013)
Mixed Forest	43	194	Smith et al. (2013)
Shrub/ Scrub	52	44	Sharp et al. (2020)
Grassland/ Herbaceous	71	80	Janowiak et al. (2017)
Pasture/ Hay	81	153	Bolstad and Vose (2005)
Cultivated Crops	82	97	Zomer et al. (2017)
Restored wetland	85	147	USGCRP (2018), Hemes et al. (2019)
Woody wetlands	90	191	USGCRP (2018)
Emergent Herbaceous Wetlands	95	164	USGCRP (2018)
Cranberry Bogs	99	109	Hemes et al. (2019)

Table D.6: Carbon Pools Table for Carbon Storage and Sequestration Model

ground carbon, below-ground carbon, soil carbon, and dead matter carbon), I choose to aggregate these carbon pools into one "total carbon" value for each LULC type. Data for the carbon pools table was drawn from a literature search, including a National Greenhouse Gas Inventory report, the Second State of Carbon Cycle Report, and others (Smith et al., 2013; Janowiak et al., 2017; Zomer et al., 2017; USGCRP, 2018; Bolstad & Vose, 2005). Where possible, values specific to Southeastern MA were used. Carbon pool estimates for restored wetlands and cranberry bogs were based on Hemes et al. (2019), who estimated the average carbon uptake over 10 years for restored peatland wetlands to be 37.56 $\frac{tons}{ha}$. In general, the focus when assembling the carbon pools table was to accurately capture the relative carbon storage capabilities of different LULC types. The carbon pool values and sources used in this dissertation are presented in Table D.6.

Appendix E

Geospatial Data Visualization Tool - Survey Evaluation Questions

The following questions were part of the Google Forms survey used to evaluate the "MA Cranberry Industry Land Use Explorer" web-tool that was distributed in May 2022. Survey instructions are also included inline.

Pre-Test Questions

- What is your name?
- What organization do you work for?
- What are your organization's primary goals?
- How does your organization currently accomplish these goals?
- What types of data or tools does your organization use to accomplish these goals?
- What are the key challenges your organization faces?
- Are there any data, information, or tool gaps that you or your organization currently face?
- On a Scale of 1-5, please indicate your level of comfort using online, web-based tools and websites.

- On a Scale of 1-5, please indicate your level of comfort reading and interpreting data in a geospatial, or map-based format.
- On a Scale of 1-5, please indicate your level of familiarity with the concept of ecosystem services.

Site Design and Layout Questions

Please navigate to the "Land Use Data Explorer" site at:

`https://cranberry-land-use-explorer.herokuapp.com/`

Please take a few minutes to explore the site, including the “Scenarios” and “Restoration Priority Index” functions on the top left, as well as the information in the panel below the map, and the information pop-ups that appear when you click on a cranberry bog or town in the map.

- On a scale of 1-5, please indicate how easy or difficult it was to navigate this website.
- On a scale of 1-5, please indicate how much you liked the design and layout of this website.
- There are many different analyses presented on this website. Below, please indicate how strongly you agree with the statement: "I liked the layout and design of this website function”
    - Scenarios
    - Ecosystem Services
    - Information tabs on the bottom
    - Town-level information
    - Bog-level information
    - Restoration priority index
- What did you like most about using this website?

- What did you like least about using this website? Was there any aspect of the website that was particularly frustrating to use?

Site Utility Questions

- How would you describe your overall experience using this website?
- Which information and analyses presented on this website did you like most, and why?
- Did you dislike any of the information or analyses presented on this website? If so, why?
- Did any of the information or analyses presented on the website surprise you? If so, please describe which information/ analyses surprised you, and why.
- What did you find most interesting about the data and analyses presented on this website?
- There are many different analyses presented on this website. Below, please indicate how strongly you agree with the statement: "I found this function useful and/ or interesting”
    - Scenarios
    - Ecosystem Services
    - Information tabs on the bottom
    - Town-level information
    - Bog-level information
    - Restoration priority index
- Would you use this tool in the context of your organization’s work? If so, please briefly describe how it might be used and how frequently. If not, please indicate why.
- What additional data, analyses, or visualizations would make this tool more useful for you and your organization?

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