Nature Based Carbon Offset Solutions in Michigan

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Executive Summary

Carbon offsets are one of the many tools for achieving carbon neutrality, particularly for sectors with high emissions, or sectors with hard-to-abate emissions. In Michigan, few resources exist on Michigan-based carbon offset acquisition or development. Thus, our project asks: what is the sequestration potential, cost, and co-benefits of carbon offset projects using cover crops on Michigan agricultural lands and reforestation of Michigan's previously forested land? And how can organizations evaluate and compare these potential Michigan-based offsets to offsets in existing offset markets?

To answer these questions we quantify the potential sequestration ability of different land types, analyze the costs given the programmatic and policy constraints of offset markets, and evaluate the social and environmental co-benefits of nature-based offsets in Michigan. This information is organized into deliverables: (1) geospatial models that identify the spatial distribution of financial costs and sequestration potential for cover cropping on agricultural land and reforestation on historically forested land, (2) a benchmarking analysis of major carbon registries, and (3) a final report which synthesizes our findings and presents an overview of carbon offsetting potential in the state of Michigan. To develop these tools we draw on a variety of methodologies, including a literature review, geospatial analysis, a sequestration analysis, a cost analysis, and a benchmarking analysis.

Prior literature that analyzes the potential for reforestation carbon offsets primarily looks at county level data. Within our analysis we present a novel approach for mapping the marginal cost per tonne of carbon sequestered at a 30-m spatial resolution. This shows that there is not only wide variation in the marginal cost of sequestration across the state, but also within individual Michigan counties. If county data were aggregated into a singular mean or median value, pockets of land with cheaper marginal costs of sequestration may be missed. We also find that 98.1% of land deemed eligible for reforestation within the state of Michigan is at an estimated marginal cost equal to or below the social cost of carbon. This means that it would be cheaper to develop a reforestation carbon offset on the land and sequester the carbon than to continue incurring the damages of leaving the carbon in the atmosphere. In addition to carbon sequestration, reforestation projects create a number of co-benefits that often do not get adequately valued, including increased recreation opportunities, air pollution absorption, wildlife habitat, and improved water retention and erosion control.

Our analysis of cover cropping as a source of carbon offsets evaluates potential carbon sequestration at the county level but employs several geographically or condition-specific inputs that set it apart from other studies. We incorporate sequestration rates derived through the USDA's standardized sample-based meta-modeling approach to estimate

potential sequestration through the adoption of cover crops on agricultural lands devoted to the cultivation of corn and soybeans, the top two crops by area in the state. Our estimates account for variability in sequestration rates based on the irrigation status of agricultural lands. In addition we calculate costs based on timescales that align with contract lengths for farmers. Through our analysis, we find that the southern half of the state has the most potential for sequestration and the cheapest offsets. While the cost of using cover crops tends to be higher than the market rate in most Michigan counties, federal incentives help lower costs and make more areas competitive. In all counties, the price of sequestering carbon through cover crops falls well below the social cost of carbon. In addition to carbon sequestration, cover crops also have the capacity to improve agricultural resilience against weather extremes due to climate change through improved water filtration, and can significantly reduce surface runoff and soil erosion.

Our analysis of six carbon markets included two compliance based markets, as well as four voluntary based. The markets were evaluated against nineteen metrics in five broader categories, then scored and assessed against DTE's priorities to inform a final ranking. Through the analysis of the four eligible markets against the nineteen benchmarks, we find that the American Carbon Registry (ACR) currently aligns best with DTE when weighted for their priorities. The key drivers of their high score was their emphasis on co-benefits.

Introduction

From municipal and state governments to corporations and educational institutions, organizations across the US are working to mitigate catastrophic climate change by developing plans to reach carbon neutrality. One of the many tools for achieving carbon neutrality is carbon offsets. Carbon offsets are defined as the sequestration of carbon in one location to compensate for emissions at another source (WRI, 2010). The use of carbon offsets are particularly relevant for businesses in industries that contain difficult or impossible to abate emissions. These industries include but are not limited to certain kinds of manufacturing, such as cement and steel, or certain kinds of transportation, such as aviation or shipping. While carbon offsets alone will not mitigate climate change, with certain safeguards they can be an effective tool for reaching carbon neutrality while also leading to numerous co-benefits. Some examples of co-benefits include air quality improvements due to reduced fires from forest management, increased biodiversity due to new reforestation projects, reduced soil erosion due to cover cropping, improved soil quality from biochar implementation, and reduced flooding due to coastal forestry projects. There are many more examples of co-benefits from carbon offset or nature based solution related projects. In most cases the financial value of these co-benefits are difficult to quantify so their value is not usually priced into the overall cost of an offset. This means that in some cases the development of a carbon offset yields more value than just the cost of the tonne of CO2e sequestered sold in an offset market.

In Michigan, few resources on state-based offsets currently exist that would help companies work towards their carbon neutrality goals while keeping their investments in the state. This applies to the development of the physical offset at the local level, as well as a market structure that allows consumers to purchase offsets generated within Michigan. The first step in alleviating these issues is by determining the offset potential of local natural lands around Michigan, and quantifying the costs of undertaking these offset projects locally. As a student consulting team for one of Michigan's utilities, DTE Energy, we ask the following questions: what is the sequestration potential, cost, and co-benefits of carbon offset projects using Michigan agricultural lands and forests? How can organizations evaluate and compare carbon offsets that exist within current active offset markets? and How do these existing offsets compare in cost and value to offsets potentially developed within Michigan?

To answer these questions we quantify the potential sequestration ability of different agricultural and reforestation practices, analyze the costs given the programmatic and policy constraints of offset markets, and evaluate the social and environmental co-benefits of nature-based offsets in Michigan. This information is organized into deliverables: (1) geospatial models that identify the spatial distribution of financial costs and sequestration potential for agriculture and reforestation offset development, (2) a benchmarking analysis of major carbon registries, (3) and a final report. In this final report we draw on a variety of methodologies, including a literature review, geospatial analysis, sequestration analysis, cost analysis, and a benchmarking analysis in order to present an overview of carbon offsetting potential in the state of Michigan.

This final report outlines our project and synthesizes the findings from all of our major deliverables. The background section describes carbon offsets and the policies influencing and framing the carbon offset market. The benchmarking analysis reviews current carbon offset market structures and aims to score these various markets by which is most suitable for DTE's needs. Our section on forestry discusses the steps involved in the development of a novel geospatial model which aims to show the amount of carbon that can be sequestered, and the cost of sequestering that carbon through reforestation carbon offsets in Michigan. The agriculture section details our methods for developing a geospatial model that estimates the amount of carbon that can be sequestered through the adoption of cover cropping on Michigan's farmlands as well as the costs associated with adopting this practice. The co-benefits section discusses the potential added localized benefits from developing these agricultural and forestry related carbon offsets in Michigan.

Background

Carbon offsets are endorsed by many environmental organizations as a tool for decreasing greenhouse gas emissions. Organizations like the Nature Conservancy support carbon offsets, and there are now industry-wide standards regarding the qualities needed for environmental offsets. According to the World Resources Institute, carbon offsets must fulfill the following five criteria for environmental integrity. Carbon offsets must be:

1. **Real:** represent an actual reduction in GHGs compared to a baseline
2. **Permanent:** Ensuring that once sequestered, the GHGs cannot be re-released into the atmosphere.
3. **Additional:** The offsets must not be an initiative that would have been implemented following business as usual, or without the incentives provided to be an offset. This can be measured in different ways including that the offsetting practice is not already mandated by law, or through project-specific cost benefit analyses that measures the difference between the most likely scenario without carbon offset incentives to the scenario where carbon market incentives are present.
4. **Verifiabl**e: Projects must be regulated and verified by a third party.
5. **Enforceable**: Using a registry of carbon offsets, each ton of carbon emissions that is offset must be linked to an owner organization. This avoids challenges such as double

counting (Goodward & Kelly, 2010).

Carbon offsets that follow these criteria are useful and cost effective in sectors with high emissions, such as the natural gas and electricity sector, or in sectors where quickly reducing emissions to zero is nearly impossible, such as aviation (Bronson Griscom, 2021)

The development of carbon offsets and nature based solutions is an ever changing industry. Financial and social incentives are constantly adjusted as new policy is implemented and different restrictions are adjusted on already existing carbon markets. A comprehensive literature review is essential to get the clearest perspective on the current state of carbon offset development within the United States. During the duration of our project alone, new policies and reports were released that could drastically change the landscape of nature based solutions within the United State and Michigan. In 2022 the Inflation Reduction Act was signed into law. This act earmarks $370 billion for climate and energy programs. It includes $20 billion for the Conservation Stewardship Program (CSP) ($3.25 billion), Environmental Quality Incentives Program (EQIP) ($8.46 billion), and three other conservation support services provided through the NRCS that contribute to mitigating climate change (*Inflation Reduction Act Investment in USDA's FPAC Programs*, 2022). While the bill contributes to the support of nature based offset solutions through investing in agricultural land management practices, it does not specifically address carbon markets or offsets (*Inflation Reduction Act: Agricultural Conservation Credit, Renewable Energy and Forestry*, 2022). The White House Council on Environmental Quality, the White House Office of Domestic Climate Policy, and the White House Office of Science and Technology Policy released a joint report titled "Opportunities To Accelerate Nature Based Solutions: A Roadmap For Climate Progress, Thriving Nature, Equity, & Prosperity" in November of 2022. This report outlines possible uses and considerations for the more than 40 billion dollars in investment toward nature based solutions that will be invested due to The Inflation Reduction Act.

The state of Michigan also released the "MI Healthy Climate Plan" in April of 2022, which outlines similar goals on climate change resilience and mitigation strategies. The Michigan Healthy Climate Plan lays out a proactive strategy and set of goals for decreasing the state of Michigan's reliance on fossil fuels. The state's goal is to achieve carbon neutrality by 2050 (*MI Healthy Climate Plan*, 2022, p. 2), and sets out goals for conserving Michigan's land and water. A key benchmark for developing nature based solutions is setting the goal by the Department of Interior's Goal of protecting 30 percent of Michigan's land and water by 2030. Along with this conservation goal, a number of strategies are included in the plan such as avoiding land conversion, encouraging sustainable forestry and developing policies that protect the state's soils and encourage carbon smart agriculture. Regarding agriculture, techniques like conservation tillage, cover cropping and reducing fertilizer use are suggested as pathways for decreasing greenhouse gas emissions (*MI Healthy Climate Plan*, 2022, pp. 47–50).

Land Use: Forests

A major reference site in our ongoing research was DTE Energy's carbon offset project on state forest land. Carbon offsets on forested land can take many different shapes but is most often implemented through increased land-management practices, afforestation, or the protection of existing forests that are under threat. The rates of sequestration from forests varies widely and it depends on the location of the forest, the particular kinds of tree species present, and the stage of growth that the forest is in. With that said, a rough estimate of forest sequestration in temperate dry forests ranged from 5-15 tons CO2/ha/year depending on tree type (Bernal et al. 2018). It is essential to be as specific as possible when determining sequestration so we can most accurately identify sequestration potential within the state of Michigan. The implementation of carbon offset projects on forest land is unique because while they are often not viewed as the cheapest method for offsetting carbon, they do contribute a wide range of co-benefits through ecosystem services, biodiversity considerations, and for people living near these lands. Determining the most accurate way to quantify co-benefits, qualitatively or quantitatively, is imperative to fully understanding the extent to which carbon offsets provide value. There is a rich history of studying forested land for this purpose and the large quantity of forested land, private or publicly owned, within Michigan makes the state a viable option for further carbon offset projects. Through the work done in our project, we intend to answer the questions: How much forested land is suitable for carbon offsetting? Where is this land located in Michigan?

Land Use: Agricultural Lands

The unveiling of the Biden's administration's climate smart agriculture plan has led to increased awareness of the potential for agricultural practices to sequester carbon and thus mitigate climate change. While this project is still in its preliminary stages–current focus is on funding pilot projects that will track carbon sequestration ability (*Partnerships for Climate-Smart Commodities*, n.d.) –scientists, nonprofits and other stakeholders have accumulated a wealth of information regarding the potential for agricultural lands to be used as a carbon offset. There is a burgeoning industry in agricultural carbon offsets registries and companies like Microsoft are including agricultural offsets into their carbon removal plan. No till/low till and cover cropping are often considered the most promising management practices for carbon offsets (Kane 2015; Plastina and Sawadgo 2021). However, taking the needs of farm business into account when considering offset prospects limit the viability of agricultural offsets in certain cases. For instance, a recent study suggests that the potential of agricultural lands to work as a carbon sink is higher than other land types like forests, but that the costs to farmers for managing the reporting process required for offsets will mean that the market price must increase from $15-$30 to $100 per credit (Alejandro Plastina et al., 2022). However, the array of co-benefits involved with increasing carbon in soils suggest that through strategic management using agricultural lands as carbon sinks can both be a valuable addition to a carbon offset portfolio that simultaneously improves crop production and soil health.

Benchmarking

Background

Carbon markets are a policy instrument where countries, organizations or other entities may buy and sell units of greenhouse gas emissions to meet their national or state-mandated limits on emissions. Carbon markets can either be compliance-based, commonly known as a 'cap and trade' system, where entities are required under government mandate to participate, or voluntary, where an organization chooses to participate in a market to reach their internal sustainability goals. Nature based offsets are allowed in certain cap-and-trade systems, however they are often subject to strict regulation. The state of Michigan currently has no policy in place to participate or create their own carbon market. Comparatively, eleven Atlantic and Northeast states currently participate in the Regional Greenhouse Gas Initiative (RGGI). At a Federal level, no carbon market has been established across the United States, and none are expected in the near future. With DTE opting to explore nature based solutions as part of their broader decarbonization goals, it was necessary to explore and assess the current landscape of carbon markets to understand which market would be best suited for DTE to purchase offsets from.

In this benchmarking analysis, we opted to evaluate and benchmark six carbon markets against 19 metrics in an interactive spreadsheet to make an informed recommendation to DTE. The metrics were then categorized into five broad categories, which were then used to create a scorecard and finalized ranking of the markets that best aligned with DTE's priorities.

Programs Selected

Six carbon markets were identified to analyze as part of the benchmarking analysis. Within the six markets were two compliance based markets, whereas the remaining four were voluntary. The two compliance based markets were used predominantly as a baseline, as

DTE did not want to enter a binding market. Rather, the company planned to opt for voluntary credits to have flexibility to meet their needs.

The two compliance markets evaluated were the California Compliance Offset Program, as well as the Regional Greenhouse Gas Initiative (RGGI). The California Compliance Offset Program was selected, as it was the first compliance market of its kind launched within the United States. More specifically, the registry acted as a supplement to the state's other programs, where nature-based offsets could be used to reduce up to 8% of a firm's annual emissions (Kim et al., 2019). In a similar vein, RGGI was chosen as the second compliance based market to evaluate due to its high recognition. Similarly; nature based solutions were used as simply a supplementary tool to the cap and trade program. Other compliance based markets our team explored included the carbon markets located within Alberta and Quebec, however - due to their international nature, we opted to focus our final selection on markets within the United States. Our team also explored potentially using the European Union's Emissions Trading System, however, upon discovery that this program was being phased out, it was not included in our analysis.

The four voluntary markets our team opted to explore were the American Carbon Registry (ACR), Climate Action Reserve (CAR), Verified Carbon Standard (VERA) and Social Carbon Methodology. ACR was selected to be evaluated since it had been in existence for over two decades. As such, there had been seven iterations of the standard by the time our team conducted the benchmarking analysis. Moreover, this program had been approved by the California Air Resources Board (CARB) in 2012 to act as an Offset Project Registry (OPR) within California's Cap & Trade System, indicating that this program had high-quality projects that met the standards of one of the premier compliance based markets in the country. The next voluntary market we chose to assess was the Climate Action Reserve (CAR), which originated in 2001 as the California Climate Action Registry before expanding to the broader North American market. The program prides itself on multi stakeholder engagement and environmental integrity, indicating that the market was an ideal candidate for this benchmarking analysis. The third voluntary market we chose to evaluate was the Verified Carbon Standard (VERA), a global framework which is informed by programs and treaties such as REDD+ and the Kyoto Protocol. This market was selected due to its global nature, as well as its size; as it is the most widely used GHG crediting program in the world. The fourth and final voluntary carbon market we selected to evaluate was the Social Carbon Methodology. Despite being a program for over twenty years, Social Carbon did not become a full standard for nature-based solutions until 2022. Moreover, the standard prided itself on not being purely focused on carbon alone, but including indicators for their projects centered on community benefits. As such, we felt it was fitting to include this program in our analysis due to this report's emphasis on co-benefits.

In choosing these four markets, our team aimed to have a selection of programs that had varied features, offset types and age to ensure that our analysis fully captured the top programs within the carbon market landscape.

Criteria Evaluated

After identifying the six carbon markets for the benchmarking analysis, we determined the metrics in which the programs would be compared against one another. Our team worked with DTE to identify nineteen metrics across the programs which are summarized into five categories: Overview, Nature-based Solutions, Features of the Program, Governance and Unique Features and Callouts.

The Overview primarily focused on basic identifiers of each carbon market, and encompasses six metrics. These metrics included who was eligible to purchase offsets, the current size of the registry, as well as locations and the average timeline for eligible projects. Moreover, this category also included details related to the average price of an offset, a priority that was determined as high for DTE.

The second category honed in on the various types of nature-based solutions that each market deemed eligible. Within this criteria included three metrics, forestry, agriculture and wetland based solutions. Despite leaving wetlands out of our scope of analysis, it remained within the benchmarking analysis as it is a potential future area of interest for DTE. Within these metrics our team populated the variety of eligible methodologies surrounding forestry and agriculture, and used the variety of eligible project types to inform scoring within this category.

The third category, Features of the Program,included four metrics which provided a more holistic understanding of the programs and included aspects such as other potential offset types that were eligible, references to co-benefits, barriers within each program as well as whether offsets/projects within the state of Michigan were allowed. A metric outlining other potential offset types was included in this section because while DTE did not express interest in these types of offset, inclusion offered easy access to a list of potential options if their priorities changed. Similarly, the metric indicating whether projects within the state of Michigan were included here, as DTE had determined that projects within the state were preferred.

The fourth category within the benchmarking analysis included five metrics related to broader governance and administrative measures surrounding the verification and administration of the registries. More specifically, this category included details on the administrative body, additionality, verification body, name of registry and ongoing monitoring efforts. As mentioned earlier, it was a priority of DTE's that any offset they purchased met WRI's criteria for integrity. As such, having carbon markets with clear definitions of additionality, ongoing monitoring, as well as verification by approved third-parties all fell within the broader umbrella of strong governance. Similarly, the ongoing monitoring metric also captured some inherent risks toward leakage and buffering.

The fifth and final category was a single metric: the use of any additional unique or noteworthy features of a carbon market not captured within the other four categories. Despite these unique features not making it into the original metric or categories, our team noted them as worth mentioning in case these features may be useful in DTE's future. The unique features ranged from a fixed percentage of benefits going towards a certain state, to extensive local stakeholder consultation and focus on community.

Once these criteria were determined, the interactive excel spreadsheet was populated with the details of the carbon markets from publicly available information on registry websites. This format provides the opportunity for DTE to understand at a glance the key differences between the markets.

SEAS SCHOOL FOR ENVIRONMENT AND SUSTAINABILITY UNIVERSITY OF MICHIGAN	**Carbon Markets Benchmarking Analysis**				
Benchmarks	**Overview**				
Markets	*Program Type*	*Who can Participate buying/selling*	*Geographic Scope*	*Number of Projects*	*Timeline*
California Compliance Offset Program	Compliance	Public/Private Entities within the state of California	United States	1620 projects in latest issuance table (*updated bi-weekly)	100 years is required for a project to meet "permanent" requirement

Table 1: *Snapshot of Interactive Excel Sheet where metric were populated*

Scoring Legend

When determining how to appropriately assess and rank the programs, we began with analyzing DTE's priorities for choosing to enter or purchase offsets from a carbon market. To that end, our team determined six main characteristics that DTE had stipulated would be important to them when deciding to enter, and ranked them as either a low, medium or high priority item. The six priorities determined were location, cost, environmental impact, additionality, verification and accessibility. Location and environmental impact were deemed to be medium priority items, additionality, verification and accessibility were deemed to be medium-high, whereas cost was determined to be the highest priority. With location, an emphasis was placed on programs which had projects that were eligible within the state of Michigan, however; some flexibility was given to include projects within the United States as a whole. For environmental impact – no specific preference was given to one type of nature-based solution over another. For additionality, an emphasis was placed on projects that had a demonstrated aspect of co-benefits integrated into their process for approving projects. With verification, DTE also wanted to ensure that any market they chose to enter had a pool of high-quality offsets that were verified through an accredited provider. Lastly, they wanted to ensure that the offsets were accessible, meaning that the offsets were easily accessible and available quickly . Through our conversations with DTE, it was determined that one of the highest priorities when choosing to enter a market was the economic feasibility and cost of purchasing offsets. To this end, our team opted to strike a balance between seeking offsets that were cost effective, yet did not cut corners on the quality of the project and offset itself.

Taking the priorities of DTE into account, we next developed a "score" for each evaluative criteria of the benchmarking analysis. Each criteria was given a score ranging from 1 to 5, with a score of 1 signifying that the program did not coincide with DTE's determined priorities for that metric, while a score of 5 indicated that the program strongly aligns or exceeds DTE's determined priorities for the metric. To allow for flexibility, as priorities and weighting of certain sectors may evolve over time, our team made the scorecard editable, so DTE staff can "plug and play" as they opt to add in new markets or adjust the scores as their priorities shift and change over time.

Next, to account for DTE's focus on cost-effective, yet high quality offsets – we decided to assign a "weight" to each section of criteria to ensure the overall score reflected DTE's priorities. Therefore our team determined that "Features of the Program" should be weighted the highest at 30%, given DTE's emphasis on securing high-quality, accessible offsets. Next, we weighted the variety of "Nature-Based" solutions accepted by each program, as well as their "Governance" standards at 25% respectively, given DTE's emphasis on verification and additionality. The general overview of each program was 15%, to ensure that the prioritization of cost was captured in this metric. Lastly, we weighed additional unique features or callouts of each program at 5%, as although these features made each program more compelling, they were not necessarily a determined priority of DTE. Similar to the scorecard, the weights can also be edited and adjusted overtime as the prioritization of certain criteria changes.

Section	Weight
Overview	15%
Nature Based	25%
Features of Program	30%
Governance	25%
Unique Features	5%

Table 2: *Overview of Evaluative Criteria and their relative weight*

After the weighting was determined, the team assigned a score of 1 to 5 for each evaluated criteria, and determined a "raw score" of unweighted points, as well as a "weighted score.".

	Overview	Nature Based	Features of Program	Governance	Additional	Raw Score (out of 85)
American Carbon Registry (ACR)						0
Climate Action Reserve (CAR)						0
Verified Carbon Standard (Vera)						0
Social Carbon Methodology						0
	Overview	Nature Based	Features of Program	Governance	Additional	Weighted Score (out of 100)
American Carbon Registry (ACR)						0
Climate Action Reserve (CAR)						0
Verified Carbon Standard (Vera)						0
Social Carbon Methodology						0

Table 3: *Sample Scorecard*

Results

Based on our analysis, our scorecard ranks American Carbon Registry (ACR) as the program that best aligns with DTE's priorities and needs, followed by the Verified Carbon Standard (Verra), Climate Action Reserve (CAR) and Social Carbon program, respectively.

Rank	Program	Raw Score	Weighted Score
1	American Carbon Registry (ACR)	67	77
2	Verified Carbon Standard (Vera)	69	76
3	Climate Action Reserve (CAR)	67	76
4	Social Carbon Methodology	56	68

Table 4: *Results table including Raw & Weighted Score from Scorecard*

Although Vera received the highest raw score of 69 points out of a possible 85 points, when adjusting for weighting based off of DTE's determined priorities, American Carbon Registry received the highest score of 77 points. The key drivers of this high weighted score were ACR's strong scoring in the Governance sector, as well as in the Features of their program. Comparatively, Vera's average cost was the lowest of all of the markets evaluated, and as a result received the highest score possible in the "Cost" metric, driving the market to have a higher raw score than ACR. The Social Carbon Methodology had the highest variety of nature-based projects eligible, however; the projects were not within the United States, and as a result, this market had a lower score in the highest weighted metric, "Features of the Program". It is important to note that the weighted and raw scores for ACR, Vera and CAR were all within one to two points of each other – indicating that each market has projects and weighting that align well with DTE's priorities. However as DTE opts to tweak and adjust the scoring, these rankings are subject to change.

Forestry

Introduction

Our analysis of carbon offset potential within Michigan is divided into two primary parts: forestry and agriculture. These two carbon offset streams are of primary focus for this report because they make up some of the greatest potential for nature-based carbon offset development within the state of Michigan. This is, in large part, due to Michigan's current land use containing large amounts of farmland and large amounts of historically forested land suitable for reforestation (LANDFIRE, 2020; Dewitz, 2021). While methodologies for developing agricultural offsets are in the nascent stages of development, forestry offsets, particularly through reforestation, are one of the most mature and well understood mechanisms for developing a carbon offset. The first ever carbon offset project was a Guatemala based avoided deforestation project in 1989 (Pyrgioti, 2023). In this section we specifically analyze forestry, whereas agriculture will be looked at in a later chapter within this report. For forestry we created a geospatial model for estimating the quantity and cost of carbon sequestration for reforestation carbon offsets within the state of Michigan.

Carbon credits are generated through forestry in three primary mechanisms: (1) avoiding increased emissions through the conservation of forested land that otherwise would have been harvested, (2) increasing carbon storage on land by generating new forested land, and (3) implementing practices for maximizing carbon storage within already forested land (improved forest management). The primary focus within this section is on the generation of newly forested land in areas suitable for reforestation. As new tree biomass grows, carbon is removed from the atmosphere and stored in several different carbon pools. These carbon pools include, but are not limited to, carbon stored aboveground in new tree biomass or herbaceous layer growth, carbon stored in ground biomass as litter or deadwood plant matter, and below ground biomass in the form of soil carbon or tree roots. These newly planted trees are considered to fulfill the requirement of additionality when they would not have otherwise been planted under business-as-usual conditions. When tree planting is additional and the removal of carbon is permanent, the basic qualities of a high-quality carbon offset are fulfilled. This understanding of forestry carbon offsets is the foundation of our project.

In the forestry chapter, we develop a framework for analyzing reforestation in Michigan by answering four primary questions. (1) Where can new trees be planted? (2) How much additional carbon can be sequestered from those trees? (3) How much will it cost to purchase the land and establish the trees on the land that we have identified as viable? (4) Taking the contract length of carbon offsets from reforestation into consideration, over what time-scale will those trees be protected? In our modeling analysis, we synthesize the answers to these questions to quantify the dollars per tonne of carbon sequestered spatially across the state of Michigan.

Methods

A primary literature review was conducted to find relevant studies that had undertaken similar methodologies related to quantifying carbon sequestration over a large spatial area. This yielded two primary reference papers that supplemented our understanding of the relevant biological systems, as well as guided some of our major assumptions. These papers are "Natural climate solutions for the United States" by Fargione et al. (2018) and "New cost estimates for carbon sequestration through afforestation in the United States" by Nielsen et al. (2014). In both of these papers, analyses were conducted for the entirety of the United States. Due to the large range of scenarios and large spatial area in each paper's analysis, the spatial specificity of their results was no finer than the county level. These papers aggregated the outputs of their models to determine total amounts of carbon sequestered under various scenarios for the entire country. In contrast to these reference papers, the analysis in our report is focused on the state of Michigan with a goal of creating a much finer spatial resolution analysis of what geographic areas are most suitable for the development of reforestation carbon offsets. Finer resolution data sources and slight differences in assumptions were used in order for us to achieve this goal within the state of Michigan.

We define land eligible for reforestation through two key characteristics. First, the land must have been historically forested and, second, it must currently be a land use type suitable for conversion back into forests. Data from the LANDFIRE Biophysical Setting (BPS) dataset is used to determine what kind of vegetation was likely present on the landscape prior to Euro-American settlement (LANDFIRE, 2020). The use of the LANDFIRE BPS for this purpose is adopted from Fargione et al. (2018), and it allows us to spatially map where these forests were historically located, and if the forests in that area were conifer, hardwood, or mixed. Ecosystem and biodiversity considerations are of paramount importance when determining which parts of Michigan are eligible for reforestation offset development. By only allowing historically forested land to be converted, we are limiting the possibility of converting all eligible land covers into forested land. If we allowed for all eligible land covers to be converted within our model setup without consideration for historic land cover, the future modeled landscape of Michigan would not align with the natural landscape of Michigan.

The next step in this analysis is to determine what land-use types are suitable for conversion into forested land if they currently exist on land that was historically forested. Current land use classifications come from the National Land Cover Dataset (NLCD)(Dewitz, 2021). The NLCD is a 30m resolution geospatial dataset updated every five years by the USGS to classify land cover across the U.S. and Puerto Rico. Classifications deemed ineligible for conversion back into forested land include: “Water” because it is not possible to convert submerged land back into forests; “Developed” because it is not economically or socially viable to convert developed land, such as homes and businesses, into forests; “Wetlands” due to concerns over there being an initial net positive release of carbon for time periods relevant to carbon offsets (Taillardat, 2020); and “Forest” due the inability for reforestation on land that is already forested. This leaves land cover classifications “Barren”, “Shrubland”, “Herbaceous”, and “Planted/Cultivated” as remaining land cover types. In the case where an eligible land cover classification overlaps spatially with a piece of land that was historically forested, we deem that plot of land eligible for reforestation within our model. Figure 1 shows the forest type distribution of land eligible for reforestation across the state of Michigan.

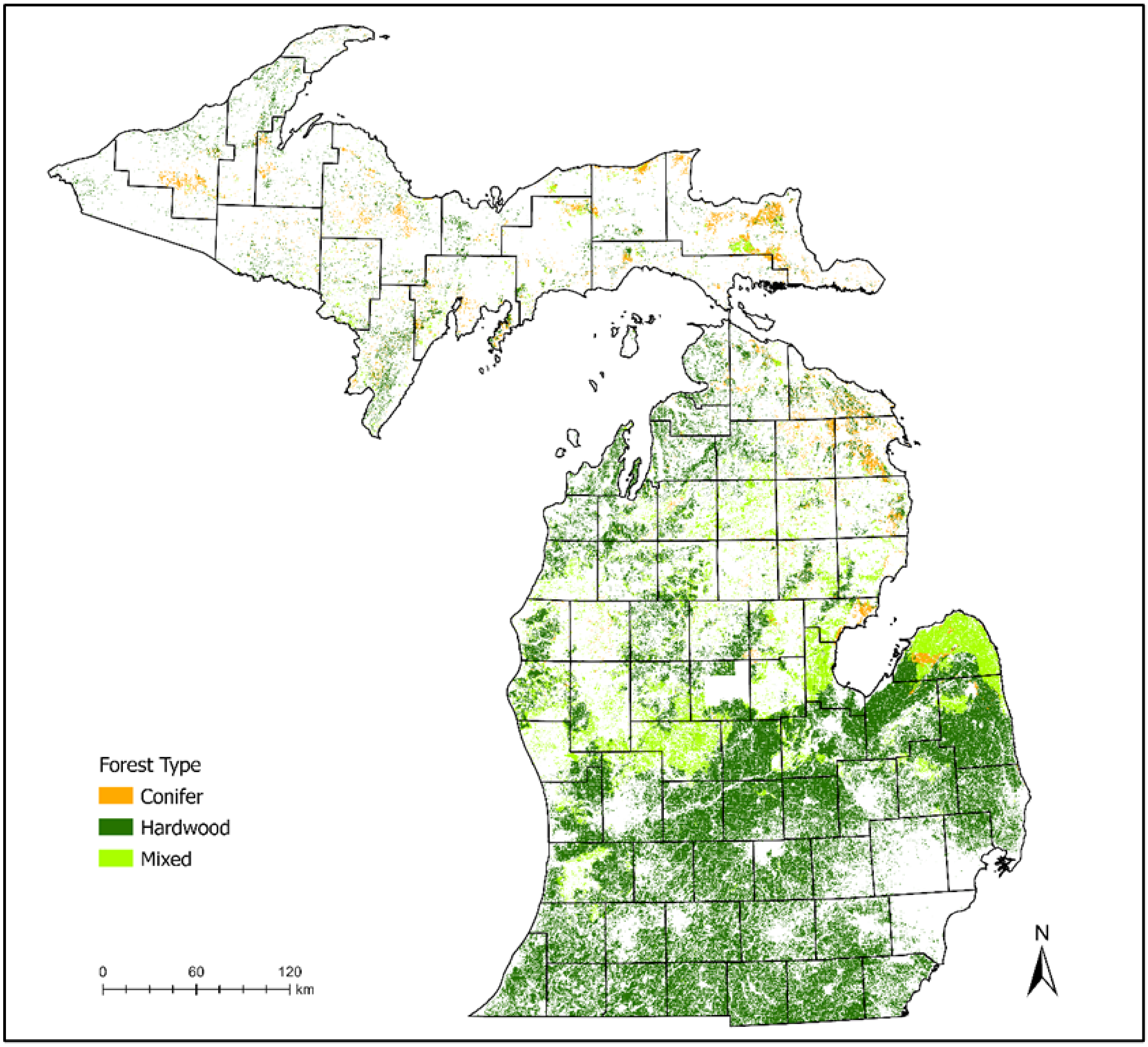

Figure 1: *Land eligible for reforestation by forest type. Forest type and the location of historical forests within Michigan comes from LANDFIRE, 2020, and classifications of land cover types eligible for reforestation come from the 2019 National Land Cover Dataset (Dewitz, 2019).*

Next, we determine the quantity of carbon that can be sequestered by trees planted in the areas deemed eligible for reforestation. Carbon sequestration by forest type is found using United States Forest Service (USFS) yield tables from "Methods for Calculating Forest Ecosystem and Harvested Carbon with Standard Estimates for Forest Types of the United States" by Smith et al. (2006). This report provides values for live tree, aboveground, and below ground carbon in tonnes of carbon per hectare at various time increments for various forest types grouped by geographic region. To align with the analysis conducted in Fargione et al. (2018), we included sequestration from live trees and soil carbon.[1] The USFS yield tables specific to afforestation were selected to account for tree establishment on currently non-forested land within the Northern Lakes States region specified in Smith et al. (2006) (Michigan, Wisconsin, and Minnesota). Total additional carbon stored on the land was determined using a 45-year time step in order to align closely with existing reforestation offset project length timelines in the voluntary offset market. American Carbon Registry, the registry recommended in our benchmarking analysis, requires a minimum of 40 years for reforestation projects (G. Burns, personal communication, October 26, 2022). The USFS tables did not include a 40-year time step so the next closest value that exceeded the 40-year threshold, 45-years, was used. In this modeled scenario we are looking at new trees being planted, and the amount of carbon stored during the first 45 years of their growth. This is an important distinction because carbon sequestration through tree growth is non-linear and tends to decrease in their rate of carbon sequestration once trees hit a certain age (Smith et al., 2006). Next, the seven forest types within the USFS yield tables were grouped into conifer or hardwood forests to match the spatial classification established by the BPS dataset. The 45-year carbon sequestration values are then averaged across BPS forest type grouping to determine a mean value for carbon sequestration. This assumption implies that there will be an equal distribution of tree species within each forest grouping, or that carbon sequestered from the plot of newly forested land will match an aggregated average value for the overall forest type. The carbon sequestration value for the mixed forest classification was determined by taking the average between the values for the conifer and hardwood forest groupings. This analysis yielded a total carbon sequestered over a 45-year period for each pixel deemed eligible for reforestation.

The final variable in this analysis is cost. In Nielsen et al. (2014), the cost of reforestation is determined by combining county level land prices, which are based on estimated opportunity cost for three primary land use types (cropland, pasture, and rangeland), and the cost of establishing forested land in each county based on data from the USDA Conservation Reserve Program (CRP). We directly referenced Nielson et al. when looking to include tree establishment cost as an input into the evaluation of cost within our model. Nielson et al. (2014) draws on 1986-1993 CRP incentives for the establishment of trees on land to estimate the cost of establishing plantations suitable to local conditions in each county. Nielson et al. (2014) intentionally uses the CRP's earlier work because the program

[1] It's worth noting that some registries, like American Carbon Registry, often suggest being more conservative with calculations of sequestration potential and do not necessarily include soil carbon in their calculations.

was most widespread during this period, thus most representative of the geographic scope of their study. We assumed that Nielson et al. had accounted for inflation and converted these estimates to 1997 dollars to match the U.S. census data they were using. To update these values for our study, we used the US Bureau of Statistics CPI Inflation Calculator to convert 1997 dollars to 2019 dollars, a year we chose as a more reliable estimate of costs rather than the following years which were acutely impacted by the COVID-19 pandemic. Tree establishment cost for each Michigan county is shown in Figure 2.

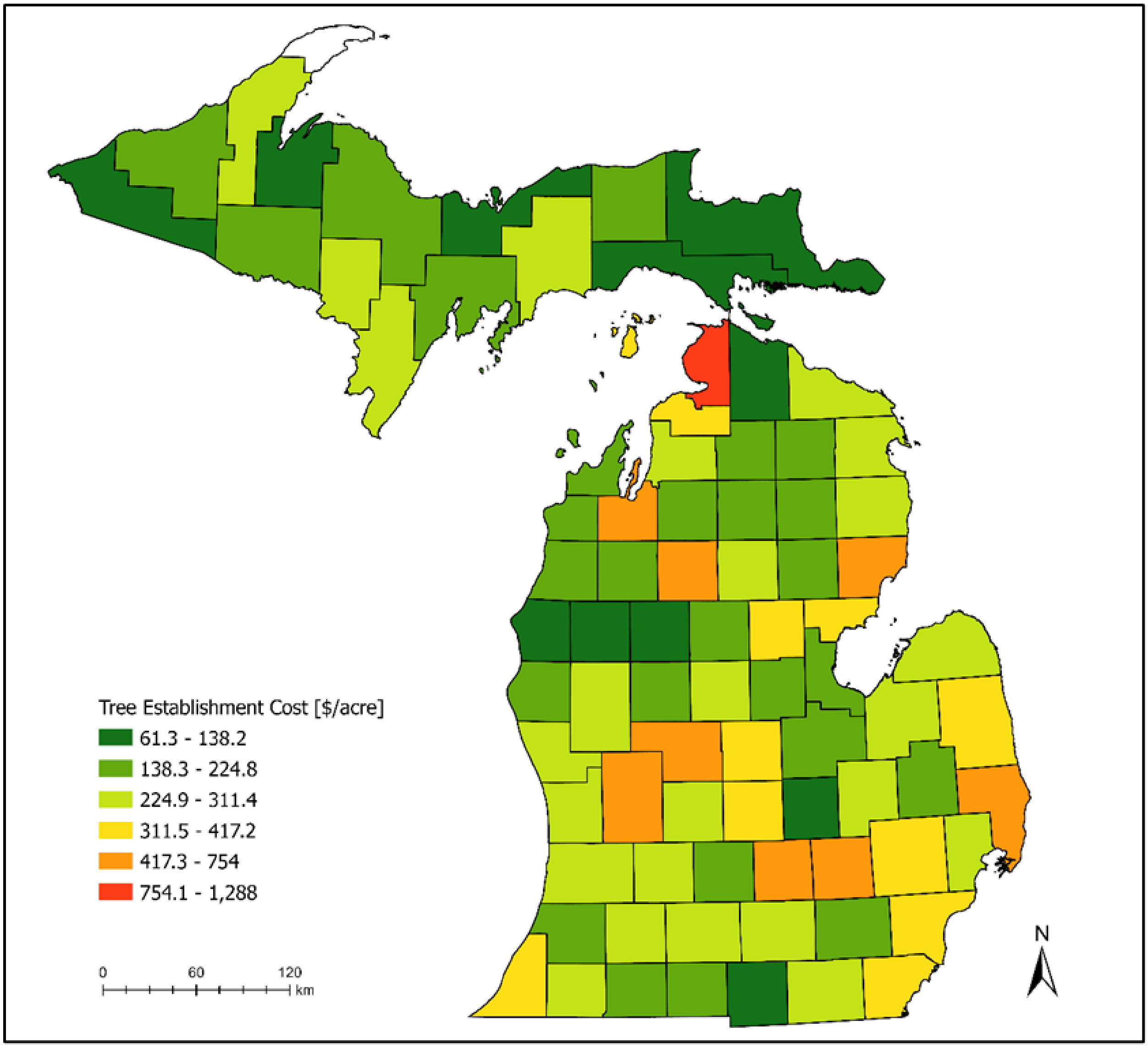

Figure 2: *Conservation Reserve Program tree establishment cost from Nielsen et al. (2014) converted to 2019 dollars.*

In Fargione et al. (2018), the cost of reforestation is determined by using a suite of marginal abatement cost curves from reference studies to determine the amount of carbon sequestered for various land use types at certain price benchmarks. These reference studies are not geographically specific to areas within Michigan, or they come from studies looking at national to global level data. In our study, we aim to account for costs at a much finer spatial scale than the county level, and with data that is specific to Michigan. We do so by using openly available data from Nolte (2020), who created a model for projecting land values across the continental United States. These modeled values come from a wide range of inputs, including but not limited to land ownership, land cover, building footprints, accessibility, flood risk, terrain, demographic, and sales records. We refer readers to that paper for a more extensive review of the methods and results of his research. The use of this data set allows for a much finer spatial resolution model (30-meter spatial resolution) to be created relative to our reference papers which focus on the county level. This finer resolution model not only shows variation between different counties, but variation within specific counties as well. Notable removals from this land include public land and Indigenous land. These were removed from our analysis due to uncertainty in the analysis of their land value. Land values from Nolte (2020) are shown in Figure 3.

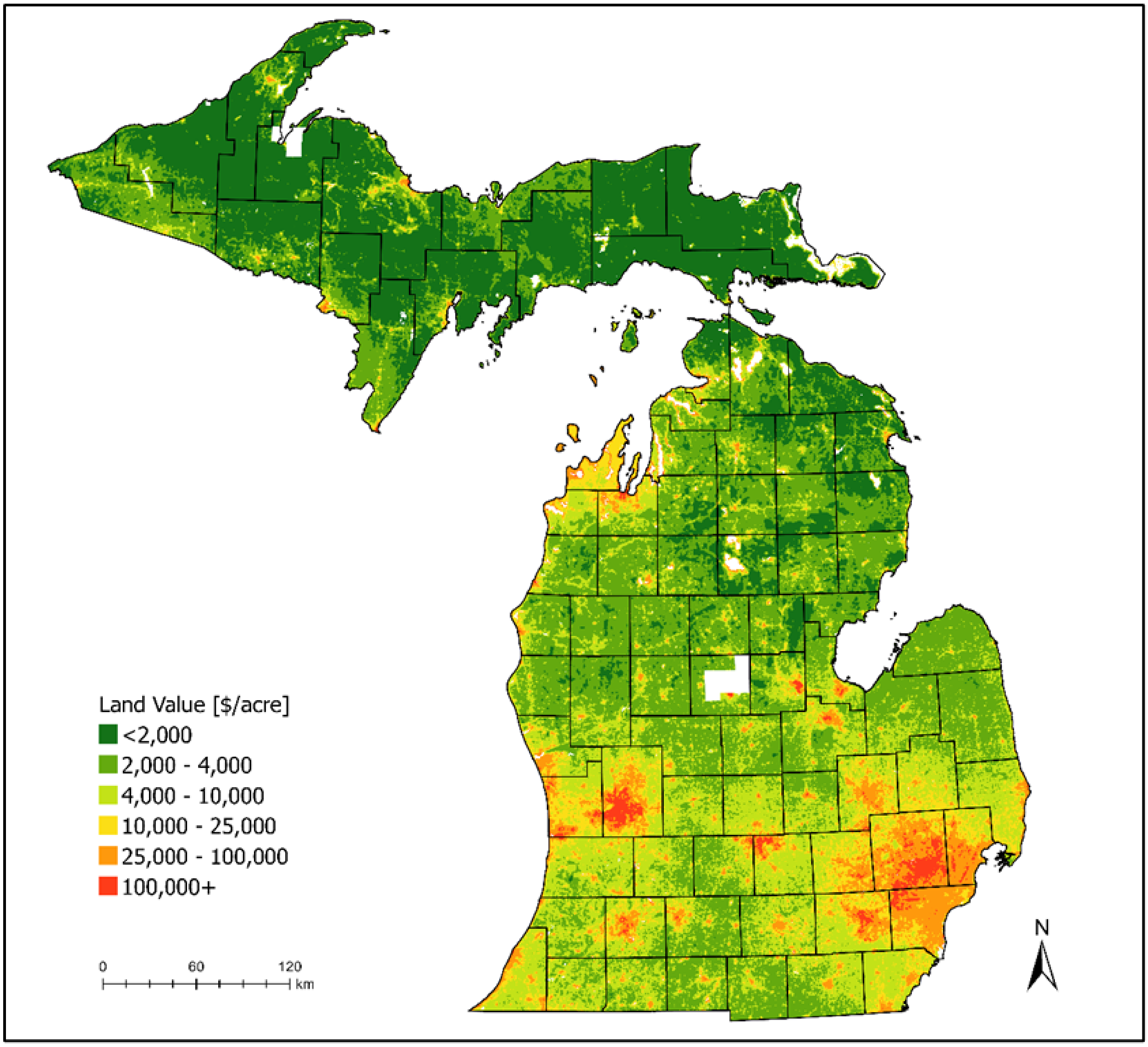

Figure 3: *Land values for the state of Michigan from Nolte, 2020.*

Results

To assemble the final estimates, we combine the cost components—tree establishment cost and land value— in order to derive a dollar amount which will be in our numerator. Next, we derive the denominator in tonnes of carbon sequestered over a 45-year period by combining the land eligible for conversion, and the amount of carbon sequestered from the USFS tables by forest type. The results of our efforts to answer our primary questions outlined at the start of our methods are shown in Figure 4.

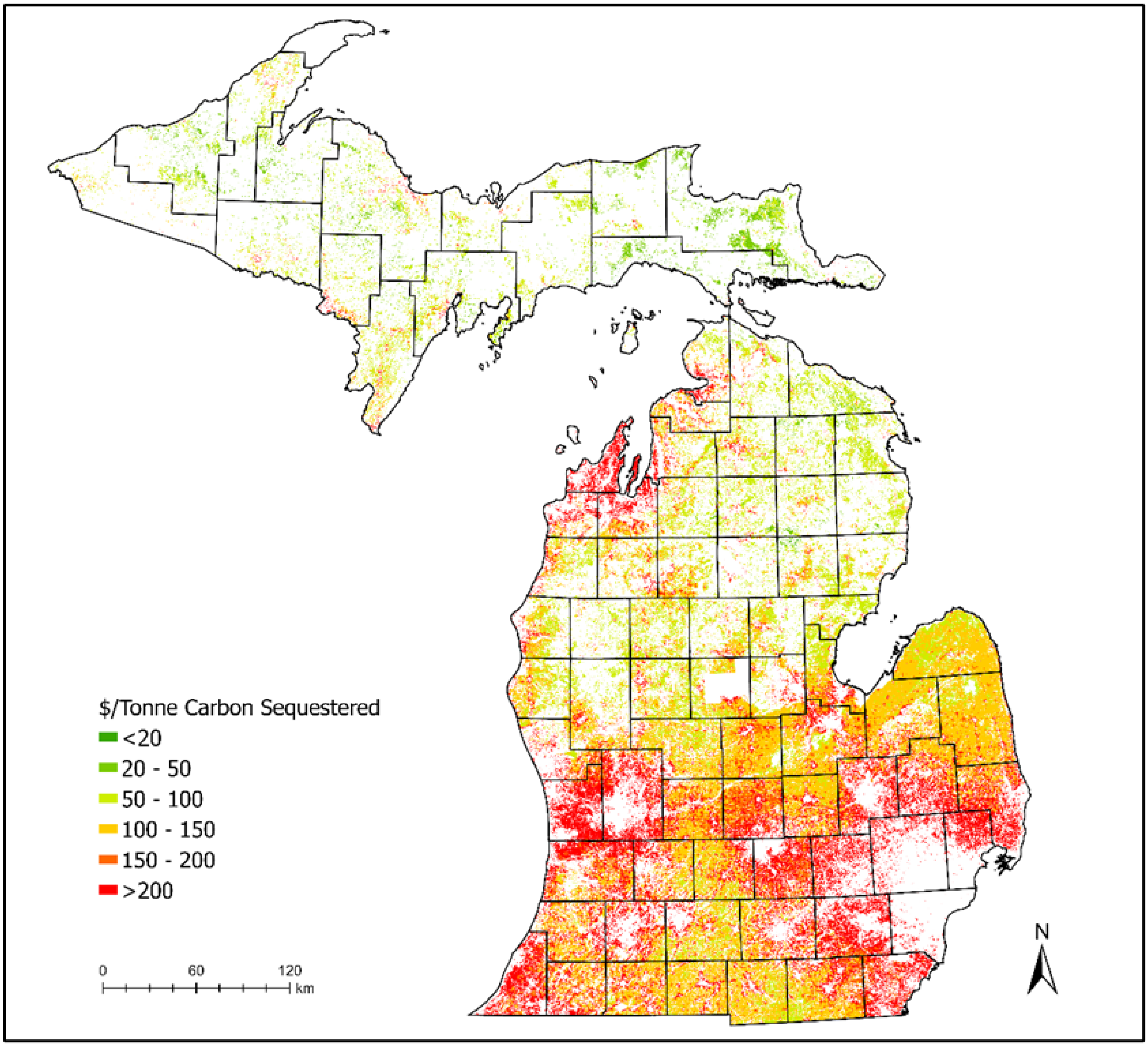

Figure 4: *The estimated cost of carbon sequestration in dollars per tonne of carbon sequestered across the state of Michigan. The 45-year timestep scenario is used to describe a normal reforestation carbon offset length under various popular carbon registries such as the American Carbon Registry (ACR) or Verra.*

After the generation of Figure 4, each pixel value for marginal cost can be paired to a particular amount of carbon sequestered over a 45-year period based on the forest type specific to each pixel. Marginal cost values can then be ordered to produce a marginal abatement cost (MAC) curve showing the quantity of carbon sequestered over a 45-year period at different marginal cost points. Figure 5 shows the MAC curve generated from the results in Figure 4.

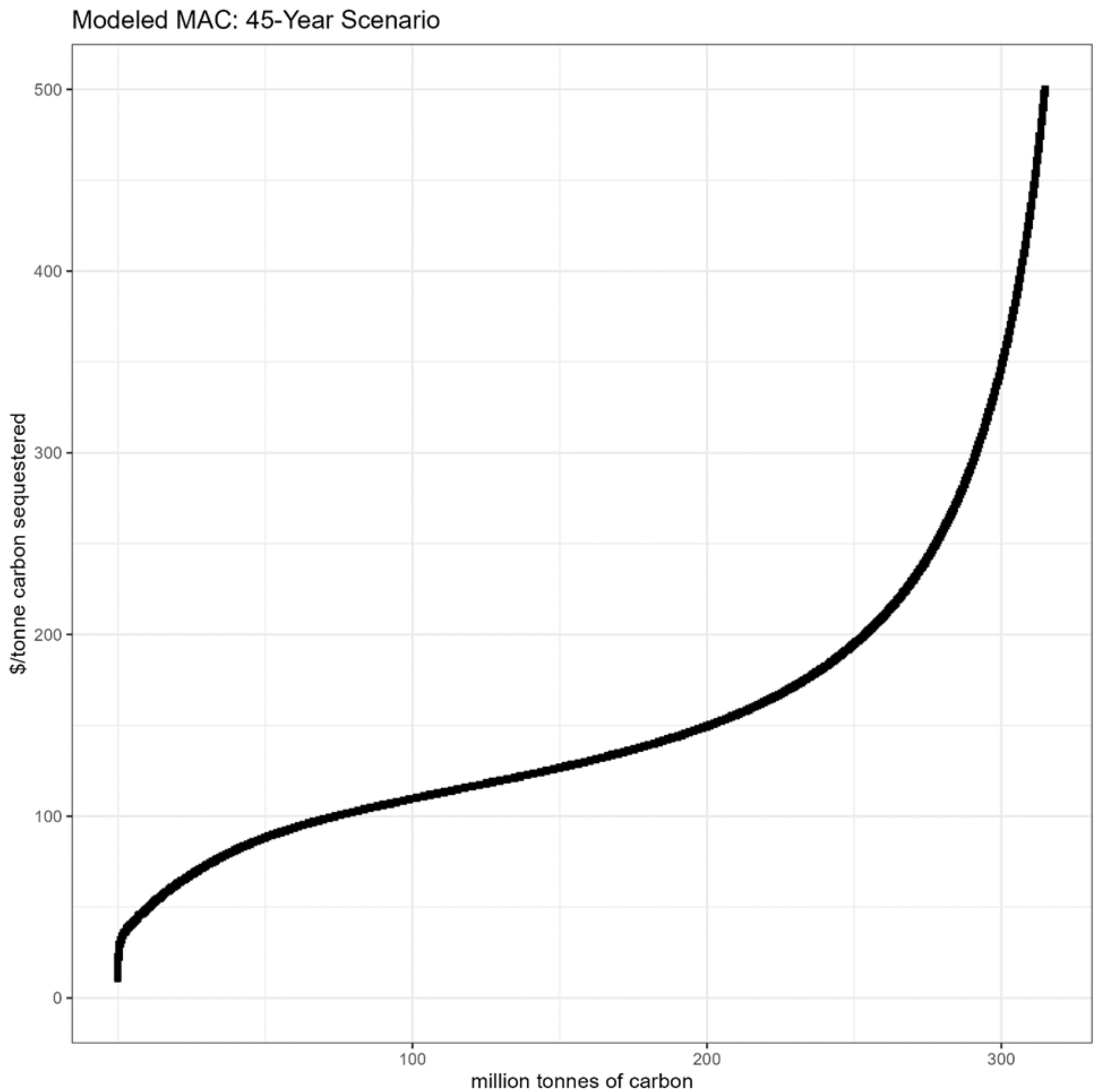

Figure 5: *The estimated marginal abatement cost curve for the state of Michigan. It is important to note that the above plot is filtered to [$/tonne] values less than 500. This is primarily for the legibility of the plot and the assumption that values above 500 $/tonne of carbon sequestered would be well above financial viability for a reforestation carbon offset.*

To better contextualize the values in map in Figure 4, and the subsequent MAC curve in Figure 5, sequestration and cost values are aggregated for various marginal cost values in Table 5. This table shows the estimated amount of carbon that can be sequestered at or below a certain marginal cost value, and what the estimated cost would be for that carbon to be sequestered under the 45-year time scenario.

Carbon Sequestration Levels and Costs at Different Marginal Costs of Sequestration

45-year Time Scenario

	Sequestration [tonnes]	Cost [$]
<=25 [$/tonne]	271,990	5,903,904
<=50 [$/tonne]	10,862,630	440,958,502
<=100 [$/tonne]	75,362,109	5,626,218,483
<=150 [$/tonne]	201,926,056	21,189,871,365
<=200 [$/tonne]	254,333,961	30,162,583,314

Table 5: *Total amounts of sequestration and the cost of that sequestration over 45 years at different marginal cost ceilings. The value for sequestration in the table above can be thought of as the value along the x-axis that aligns with a particular marginal cost ceiling (25 [$/tonne], 50 [$/tonne], 100 [$/tonne], etc.) on the y-axis. The cost value then comes from the area under the MAC curve from zero to where this intersection occurs.*

The primary advantage of our analysis relative to our main reference papers, Fargione et al. (2018) and Nielson et al. (2014), is the development of spatial heterogeneity for marginal cost within each county across the state of Michigan. To highlight this advantage, we select four Michigan counties with relatively high spatial heterogeneity for marginal cost. These counties are Bay, Lenawee, Ogemaw, and Osceola, shown in Figure 6.

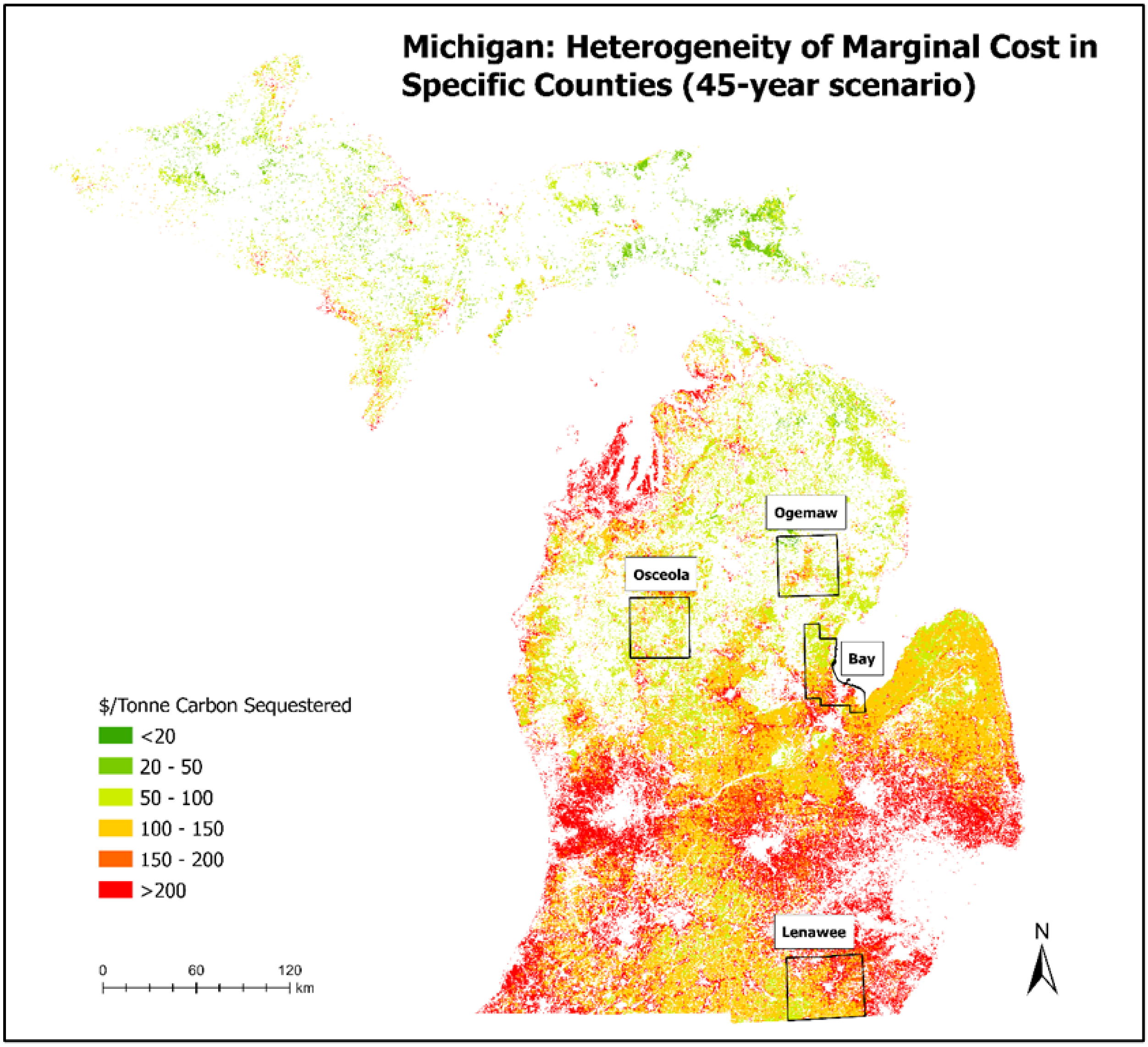

Figure 6: *Specific counties within Michigan highlighted for their distribution of low and high marginal costs of sequestration.*

In each of these counties we see dark to light green pixels indicating lower marginal costs of carbon sequestration, and red to orange pixels indicating higher marginal costs of carbon sequestration. The MAC curves are generated for each county in Figure 7 to emphasize this relationship more clearly.

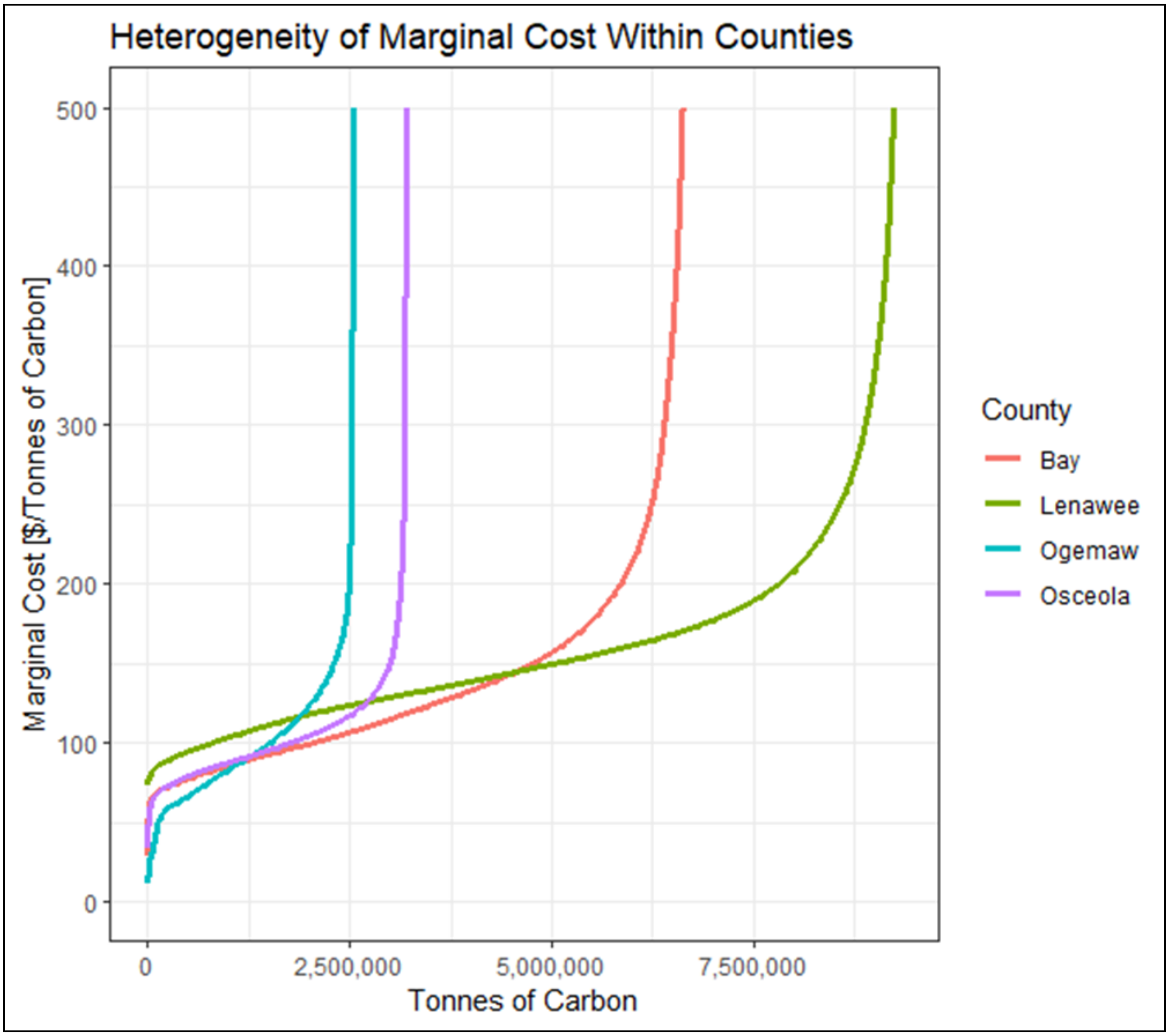

Figure 7: *Specific counties within Michigan highlighted for their distribution of low and high marginal costs of sequestration.*

If county-wide average or median values were used to determine which counties were suitable for reforestation offset development, then large pockets of suitable land are likely to be missed. Using mapping tools, as seen in Figure 4, combined with MAC curves, as seen in Figures 5 and 7, we can determine spatially where reforestation offsets can be developed at the cheapest cost, how much carbon can be sequestered from that specific site, and what the sum of the costs and carbon would be over a certain time step.

Discussion

In many ways this analysis is exploratory and should be used as a reference guide for decision-makers looking to develop reforestation carbon offset projects on private land within Michigan. The primary advantage in this analysis, relative to our main reference papers with similar methodologies, is the increased degree of spatial specificity in our results, especially within individual counties. In figure 4, we observe substantial variation within many counties' marginal costs of carbon sequestration. This relationship is made even more clear within Figures 6 and 7, where four Michigan counties — Ogemaw, Osceola, Lenawee, and Bay — are highlighted to emphasize this heterogeneity.

The new approach to cost in our analysis, using the land value data from Nolte (2020), allows for these new insights to be derived. Land near urban areas or close to desirable destinations, such as lakes, sand dunes, state parks, or mountains, have higher land values. With that said, many counties are large and have pockets of this high value land while also having lower value areas scattered throughout. This creates regions of high and low marginal costs for carbon sequestration. If median or average values were used for each county, it is possible that certain continuous land areas with lower marginal costs of sequestration could be missed. This would be due to pockets of high land value areas increasing the overall average or median marginal cost within a specific county. Looking at figure 4, we can see that the areas of cheapest offset potential are located in the northeastern part of the lower peninsula and many parts of the upper peninsula of Michigan. This makes sense due to these areas being lower in population density and containing land cheaper for conversion. With that said, there are some noticeable outliers where pockets of high cost of carbon sequestration areas are located within these generally low-cost geographic regions. That heterogeneity in marginal cost exists in some of the most remote parts of Michigan further stresses the importance of the spatial specificity displayed in this model.

Due to the size of DTE Energy, and their potential needs for purchasing carbon offsets, it is likely for them to purchase or develop 10,000 - 50,000 offset credits at a time. Figure 5 and Table 5 show that there are substantial amounts of carbon available for sequestration through reforestation within Michigan. For reference, one tonne of carbon, what is used in our results, is equivalent to 3.67 tonnes of CO_2e, the units of a carbon offset. With that said, for a reforestation carbon offset project to be developed, it likely must be almost entirely spatially continuous. This is because in practice, an offset developer looking to produce reforestation carbon offsets cannot pick and choose small geographic locations scattered around Michigan for planting trees due to logistical and management constraints. For reference, in 2022 the Michigan DNR completed the development of the Big Wild Forest Carbon Project, which involved 100,000 acres of state forest land to be used for generating carbon offset credits through sustainable forest management practices (Michigan DNR). This is the first carbon offset development project on state forest land in the nation and has a project length of 40 years. DTE Energy has already committed to purchasing the first 10 years of carbon offset credits generated from this project. The success of the Big Wild project led to the Michigan DNR beginning the development of a similar 120,000 acre project split between the northern lower peninsula and the northwestern tip of the upper peninsula, named the Wolverine-Copper Country Forest Carbon Project. While the size of these projects leaves uncertainty in the total tonnes of carbon sequestered in each, it shows the growing momentum for large scale, continuous, forestry carbon offset projects being developed within the state of Michigan.

It is important to further emphasize that the units in our results, dollars per tonne of carbon sequestered, is not equivalent to the units of a carbon offset, dollars per tonne of CO_2e. The atomic weight of carbon is around 12 amu while the atomic weight of CO_2 (which can also be thought of as CO_2e for comparison purposes) is around 44 amu. A conversion can be done for comparison purposes by multiplying the dollar per tonne of carbon amount by 0.27 (the atomic weight of carbon divided by the atomic weight of CO_2). We can then compare the results shown in the previous section to different registry or offset market benchmarks to see how competitive these hypothetical offsets would be on different offset markets.

CO2e Sequestration Amounts and Costs at Different Benchmarks

Mean Foresty and Land Use Offset Cost in 2019

	Benchmark [$/tonne]	Sequestration [tonnes]	Cost [$]
CA Compliance Offset Market	11.56	12,547,333	449,862,034
American Carbon Registry	5.87	190,409	3,562,477
Climate Action Reserve	8.12	1,446,461	36,645,639
Verra	3.14	1,981	22,276

Table 6: *Benchmark values for different registries or offset markets come from Ecosystem Marketplace's mean forestry and land use offset cost values in 2019 (Ecosystem Marketplace Public Carbon Dashboard). These values come from a combination of market research, and a voluntary survey given to developers, investors, and other relevant parties (Donofrio et al. 2021). Sequestration and cost values within the table indicate the modeled quantity of* CO_2e *that can be sequestered at or below the benchmark price, and the cost of sequestering that much* CO_2e *at or below the benchmark price.*

Table 6 allows us to contextualize the results of our analysis within the broader carbon offset market to see if our modeled reforestation carbon offset potential within Michigan would be financially competitive when compared to other forestry offsets. These registries or methodologies are used in this comparison because they represent popular, primarily U.S. based offset development in the case of the CA compliance offset market, Climate Action Reserve, and the American Carbon Registry which is not exclusively U.S. in its offset development but prefers U.S. or North American offsets. Verra is also included because while it is international in scope, it is one of the more popular standards for carbon offset development. We refer to the later section in our report on benchmarking for a more extensive review of these registries and markets.

As we can see from Table 6, offsets developed within the U.S. tend to come at a higher cost than offsets developed abroad. With that said, there is growing demand from U.S. based companies to participate in offset projects located within the U.S.. This is due to their desire for offsetting within the country, or closer to the source of emissions that are being offset. It is also important to note that the categorization of forestry and land use being grouped together means that some cheaper offsets, such as forest management and avoided deforestation, will bring the average cost down relative to more expensive reforestation offsets. Reforestation offsets, while often more expensive than other forestry related offset types, tend to lead most offset categories when it comes to net carbon offsetting potential in the U.S. (Fargione et al. 2018). They also provide added value through co-benefits of new forest generation. Co-benefits are discussed in more depth within a later section in this report.

Finally, if we compare our modeled prices for the cost of sequestration to the new EPA estimates for the social cost of carbon, around 190 dollars per tonne of CO_2e which is equal to around 697 dollars per tonne of carbon, we find that 98.1% of all land area deemed eligible for reforestation within our model could be reforested at or below the social cost of carbon. This means that most of the land eligible for reforestation carbon offsets can be developed to sequester carbon at a cheaper cost than the current damages incurred by the carbon remaining in the atmosphere.

As mentioned previously, this analysis should be used as an exploratory tool for determining where reforestation carbon offset projects may be cheapest to develop within the state of Michigan. Like any modeling analysis, it is important to recognize any key assumptions or shortcomings that could be improved upon in future work. A key input in this analysis is the modeled land value dataset from Nolte et al. (2020). By using this data, we assume that private property owners would agree to sell or alter the land use of their land at the price of the land's value. This negates a wide number of factors that may influence a landowner's perception of their land value such as sentimental reasons, or a desire to continue their use of the land in a specific way, such as farming. We also do not factor in how land values may change as new forests are planted for carbon offset projects in the future. If land value is a function of land use type and proximity to certain geographic features, it is reasonable to assume that if a reforestation offset project was developed in a certain region it might have an impact on surrounding land values that may also be eligible for reforestation. It is also important to emphasize the importance of the 45-year time period used in our model. This number is used primarily as a conservative estimate for the amount of carbon sequestered over the lifespan of a reforestation carbon offset project, but in some cases these types of projects can have up to an 80-year contract length. In our current modeling framework an 80-year time length scenario would mean an increase in sequestered carbon at the same cost, thus leading to more positive results in terms of the dollars per tonne of carbon sequestered shown in our results section. We show in this analysis that there is ample land suitable for the development of reforestation carbon offsets, and much of this land may be possible for development at a competitive price relative to other U.S. based reforestation carbon offset projects. We recommend further investigations on a site-by-site basis for future research and primarily aim to offer a broad overview of viability with the results in our report.

Agriculture

Introduction

Using agricultural land management for carbon offsets is a practice that is still in its nascent stages in the United States. Only one major registry, Climate Action Reserve, has approved protocols for soil sequestration through agriculture, though Verra has developed preliminary protocols which are still awaiting final authorization. At the federal level, legislators have demonstrated interest in researching and regulating this market. After several prior attempts, the Growing Climate Solutions Act was signed into law by President Biden as part of a larger omnibus package passed at the end of 2022. The law creates a voluntary certification program for carbon offset registries, and provides technical support to organizations involved in the development of agricultural and forestry offsets.

Despite relatively slow movement at federal and registry levels, developers and companies have already begun investing in the agriculture offset market. Companies like Land O' Lakes are developing their own offset protocols and have already made significant investments in agricultural offsets. Developers have been quick to jump on this opportunity as well. Indigo Ag is perhaps the most well known developer of agriculture offsets in the voluntary market.

They use the Climate Action Reserve protocols to develop offsets with the farmer in mind. While Verra's protocols have not yet been finalized, some developers are already purchasing and selling offsets from farmers using their protocols (B. Massie, personal communication, February 9, 2023).

Even as interest in the use of carbon offsets grows, the science underlying the use of different agricultural methods is mixed. Despite some evidence of enhanced carbon sequestration associated with the adoption of no-till agriculture, more recent studies indicate that no-till fields actually hold less carbon than conventionally-tilled fields in soil horizons below traditional sampling depths, offsetting the increase in carbon storage at shallower depths. Additionally, no-till practices have been documented to increase N20 emissions during at least the first decade of their implementation, suggesting that no-till methods would need to be applied continuously for at least 10 years in order to yield any net greenhouse gas sequestration. Given that current agricultural offset contracts vary in length with some being as short as 5 years, this 10 year minimum is not guaranteed to be met. Due to these limitations of no-till agriculture as a reliable carbon sequestration practice, Fargione et. al (2018) do not include it in their analysis and we have similarly decided not to focus on this practice in our study.

Instead, we analyze the use of cover crops as a method for sequestering carbon and offsetting emissions. Cover cropping is the practice of planting a crop during the winter period when farmlands are typically left fallow. Like with no-till, some scientists still remain skeptical about the ability for cover crops to be used as a carbon offset (J. Blesh, personal communication, 2021) but others like Fargione (2018) are more hopeful. Cover cropping creates an array of environmental benefits including decreasing nitrogen run-off and leaching as well as increasing soil organic matter, which is where carbon is sequestered and stored in agricultural lands (King & Blesh, 2018; Poeplau & Axel, 2015, p. 34). Moreover, given the existence of markets for carbon sequestered through cover cropping and established methods from the USDA to quantify the ability of cover crops to sequester carbon and decrease the release of nitrous oxide, we decided to analyze their potential as a carbon offset measure. Specifically, our study asks for the state of Michigan::

1. What areas of agricultural land currently employs cover cropping?
2. How much carbon can be sequestered by adopting cover crops in areas that do not currently do so?
3. How much will it cost to sequester carbon through the adoption of cover crops?

To answer these questions, we analyze the impact of implementing cover cropping in tandem with several key conservation practices for Michigan's top two crops: corn and soy (USDA, 2017). Like our analysis for forestry, we refer closely to Fargione et al.'s study on nature-based climate solutions, particularly the section on cover crops. Our analysis deviates from this reference study in several key ways. Firstly, Fargione et al. include crops that are not cultivated in our geographic region, such as cotton and rice, so we have excluded these crops from our study. In addition, we take a more geographically specific approach than Fargione; the details of this are described in our methods section below.

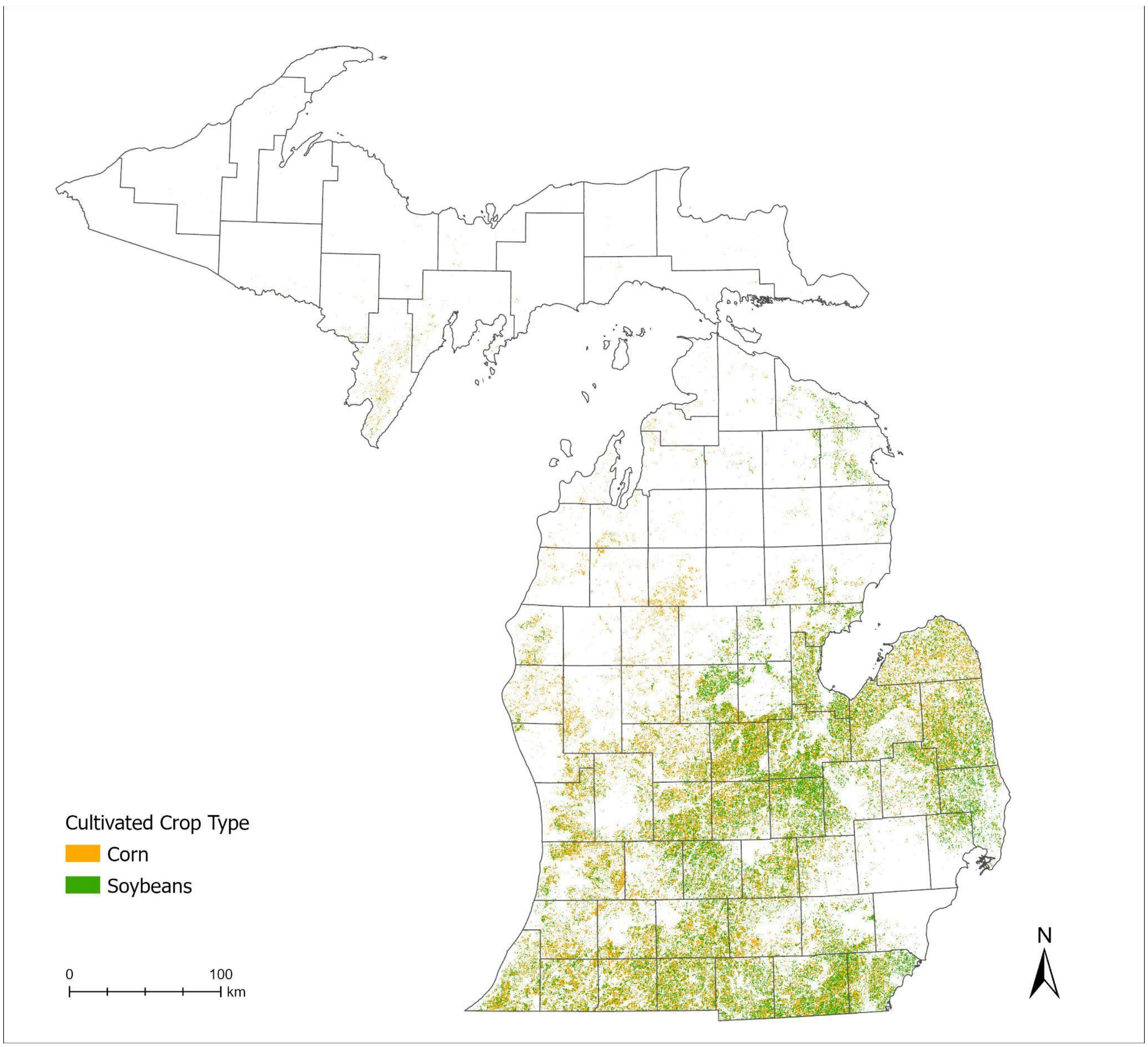

Figure 8: *Distribution of corn and soybean fields in the state of Michigan. Map is derived from the USDA Cropland Data Layer (2022).*

Methods

Our analysis provides a spatially informed calculation of carbon sequestration. Fargione et al. (2018) relies on a sequestration rate developed in a meta-analysis using the rate of sequestration from cover crop types applied on a wide variety of crops across the world. To achieve greater regional specificity, we utilize a United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) tool for estimating greenhouse gas sequestration through NRCS conservation practices. This tool, the Carbon Management & Emissions Tool-Planner (COMET-Planner), estimates greenhouse gas sequestration using a sample-based, metamodeling approach and the USDA entity-scale inventory methods. The resulting sequestration estimates represent the average sequestration impact of adopting the specified agricultural practice over baseline conditions across a range of soil, climate, and cropland management types. COMET-planner provides sequestration rates (CO2 equivalent per acre per year) for each of 8 fixed implementations of cover cropping that align with the NRCS's conservation incentives programs:

1. Add Legume Seasonal Cover Crop (with 50% Fertilizer N Reduction) to Irrigated Cropland
2. Add Legume Seasonal Cover Crop (with 50% Fertilizer N Reduction) to No-Till Irrigated Cropland
3. Add Legume Seasonal Cover Crop (with 50% Fertilizer N Reduction) to No-Till Non-Irrigated Cropland
4. Add Legume Seasonal Cover Crop (with 50% Fertilizer N Reduction) to Non-Irrigated Cropland
5. Add Non-Legume Seasonal Cover Crop (with 25% Fertilizer N Reduction) to Irrigated Cropland
6. Add Non-Legume Seasonal Cover Crop (with 25% Fertilizer N Reduction) to No-Till Irrigated Cropland
7. Add Non-Legume Seasonal Cover Crop (with 25% Fertilizer N Reduction) to No-Till Non-Irrigated Cropland
8. Add Non-Legume Seasonal Cover Crop (with 25% Fertilizer N Reduction) to Non-Irrigated Cropland

Using a diversity of practices aligns with current trends in the agricultural offset market. Offset developers often ask farmers to implement one or more different practices to sequester sufficient carbon to be viable in the offset market. Despite mixed evidence for its efficacy as a carbon sequestration practice, no till/low till is often considered a baseline practice for eligibility (B. Massie, personal communication, February 9, 2023), so our model uses scenarios that include no-till as a factor in cover crop implementation. Cover crops in soy-corn rotations tend to be non-legumes, primarily cereal crops such as wheat, rye or oat (*Cover Crop Economics: Opportunities to Improve Your Bottom Line in Row Crops*, 2019). For this reason, we selected the COMET-Planner tool implementations based on the adoption of non-legume cover crops. COMET-Planner also considers irrigation status as a factor in cover crop implementation. Thus, we used the COMET-Planners' sequestration coefficients for the following two implementations: 1) Add Non-Legume Seasonal Cover Crop (with 25% Fertilizer N Reduction) to No-Till Irrigated Cropland and 2) Add Non-Legume Seasonal Cover Crop (with 25% Fertilizer N Reduction) to No-Till Non-Irrigated Cropland.

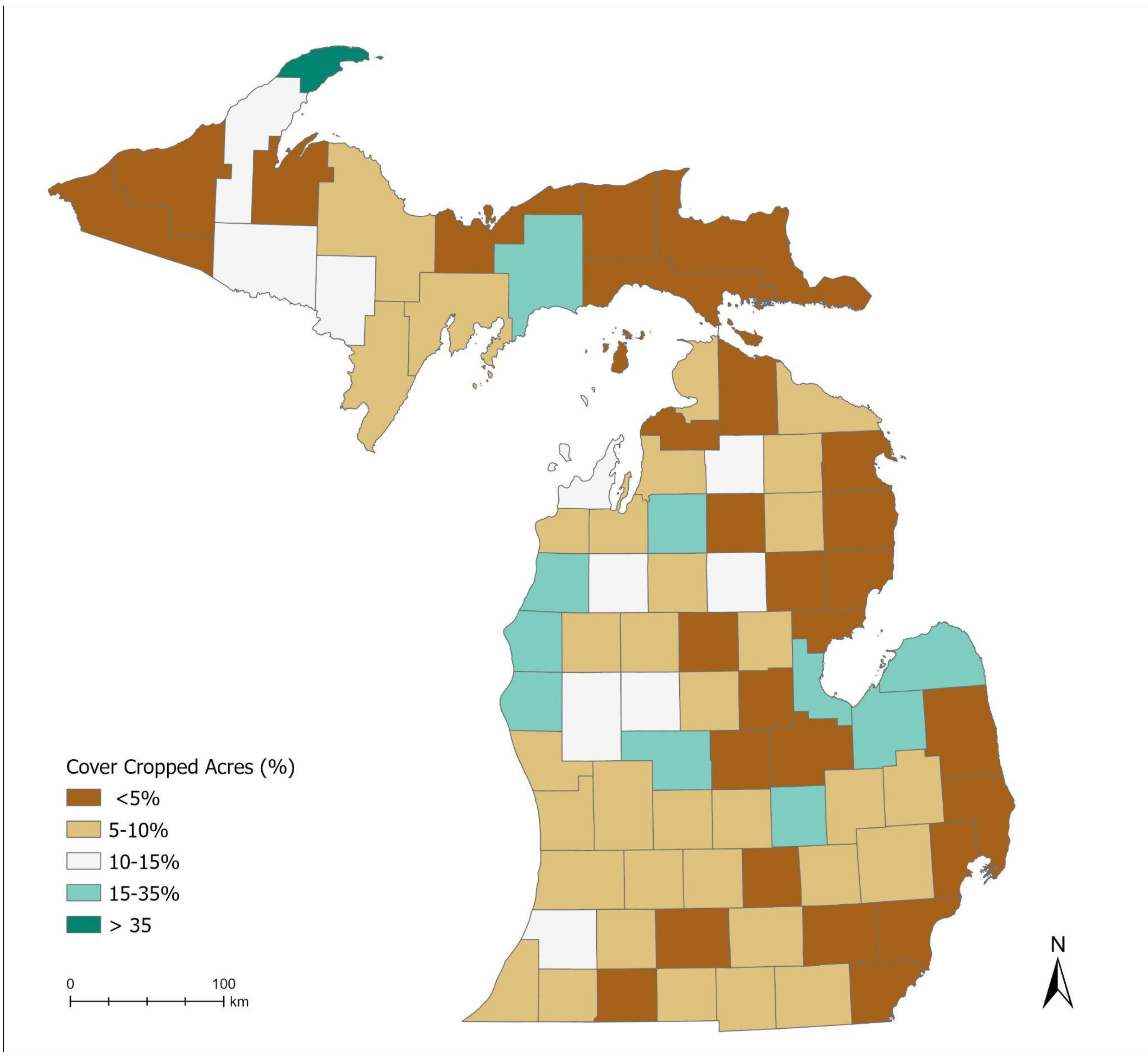

Figure 9: *Rates of cover crop uptake for the state of Michigan. While some areas, like the northeastern part of the state around Lake Huron, or around the "Mitt," have high rates of cover crop uptake and relatively high*

rates soybean and corn production, other areas with large acreages of corn and soybean, such as Hillsdale and Lenawee County along the Southeastern border of the state have low rates of cover crop update. This low uptake in regions of high production offer much potential for using cover crops as a carbon offset.

Calculating Estimated Sequestration at the County Level

To estimate carbon sequestration at the county level, we used a variety of data sources. From the USDA Cropland Data Layer (CDL), we mapped the area and distribution of corn and soy cultivation across the state of Michigan (Figure 8). Next, using the USDA 2017 Census of Agriculture data on current cover crop uptake per county (Figure 9), we estimated the area of corn and soybean cultivation that is not currently under cover crops to derive the potential for additional carbon sequestration through the adoption of this practice.

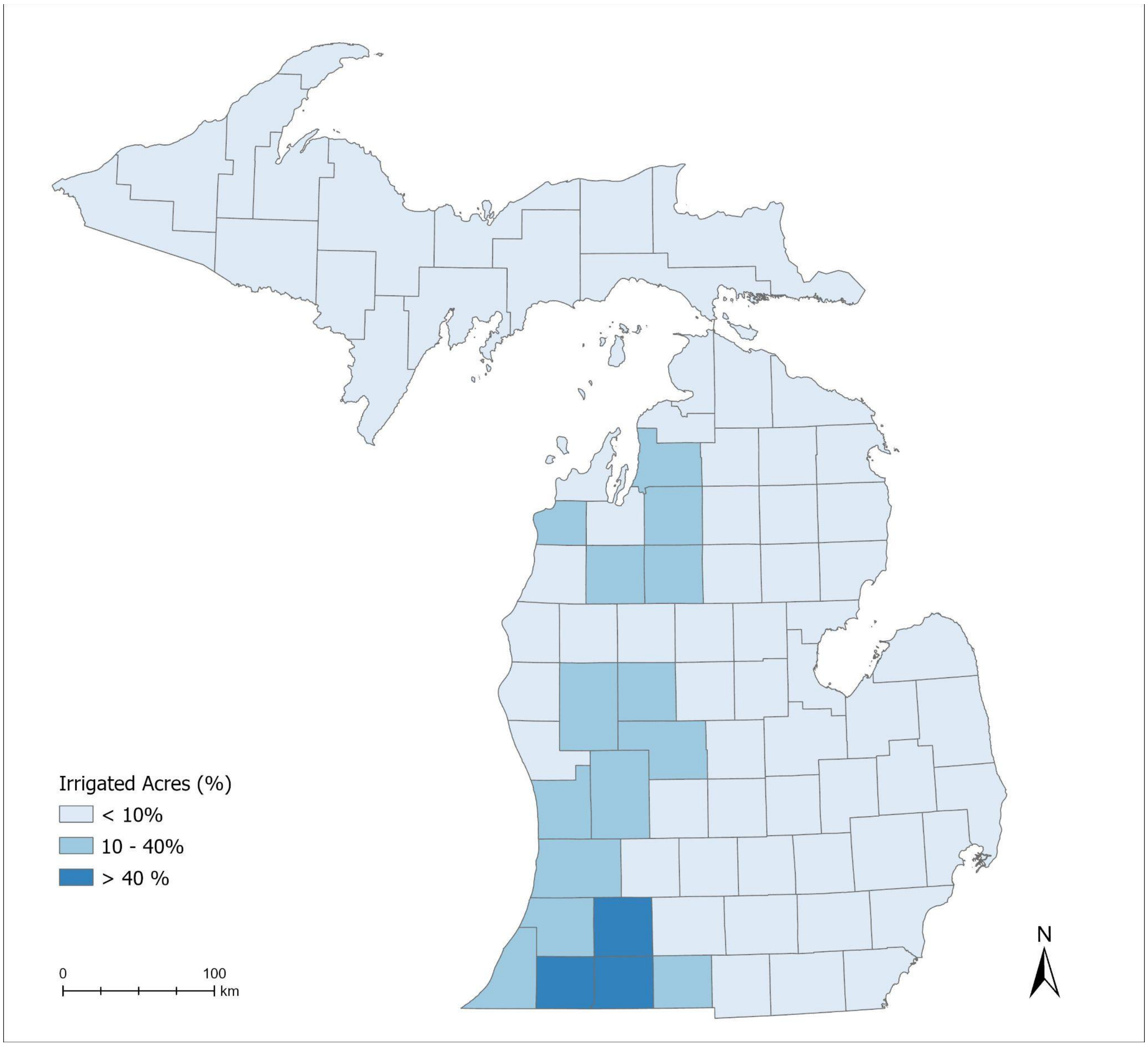

Figure 10: *Irrigation rates for the state of Michigan. Western Michigan tends to have higher rates of irrigation with the highest rates of irrigation clustered in Southwestern Michigan. These rates come from the 2017 Census of Agriculture..*

Because sequestration rates differ depending on the irrigation status of the land, we then estimate the amount of irrigated and non-irrigated non cover cropped lands in each county based on the percent of irrigated land as defined in the 2017 Census of Agriculture. We then estimate sequestration rates through applying the COMET planner calculators' sequestration rates for all irrigated and non-irrigated soy and corn acreages to develop an estimated sequestration potential for each county. A meta-analysis on cover crop impacts suggests that sequestration rates are linear, at least during shorter time spans of less than 20 years, so we assumed that the rate provided through the planner could be used annually (Poeplau & Axel, 2015). Indigo Agriculture, the forerunner in agriculture soil carbon offsets, requires farmers to sign a 5-year-contract to be considered an offsets, so in our calculations of sequestration rates, we estimate rates based on a 5-year-time period.

Deriving Cost

Our model for estimating costs also differs from the methods used by Fargione. Fargione's estimates of cost are based on studies that take place in the Mid-Atlantic and the South; due to these geographic differences, farming conditions are likely to differ in the Midwestern state of Michigan. Based on estimates found in the literature, Fargione et al. estimate high, mean, and low values for the net impact of cover cropping on farm-level profitability for a select number of crop types. The values encompass a range from slightly negative to significantly positive profitability impacts due to the variety of cover crop implementations and their associated impact on farm profitability. Positive net impacts on profitability can result from increased crop yield and/or reduced need for chemical inputs, such as fertilizer. While a sound approach, given that regionally specific data was limited, we took a more streamlined approach to estimating cost.

Aside from case studies, reliable studies for the Midwest were difficult to find so we used a study focused on supporting farming nationally: Cover Crop Economics: Opportunities to Improve your Bottom Line in Row Crops (2019), a technical bulletin produced by the Sustainable Agriculture Research & Education (SARE), to develop our estimates for the costs and benefits of implementing cover crops on corn and soy farms. We utilized SARE's basic costs scenario which includes the costs of seeds as well as the additional benefits of reduced costs of fertilizer, weed control and erosion control, and additional income from increased yields over a 5-year-time period for corn and soy, respectively. The study shows a total of estimated costs for year one, three and five, based on low end estimates for input savings. For our model we average the costs of years one and three and three and five to derive cost estimates for year two and four. Because these costs are accrued annually, we then discounted the costs for each year by 3 percent, a commonly used discount rate in policies and federal legislation. We assume that management changes will take place starting the year following (in other words, we discount beginning with the costs for the first year).

This estimated cost of cover cropping was then applied to corn and soy acreages to estimate the costs of sequestration per tonne of carbon dioxide equivalent for corn and soy in each county. We then combined these estimated sequestration rates to develop an aggregate cost per county.

Results

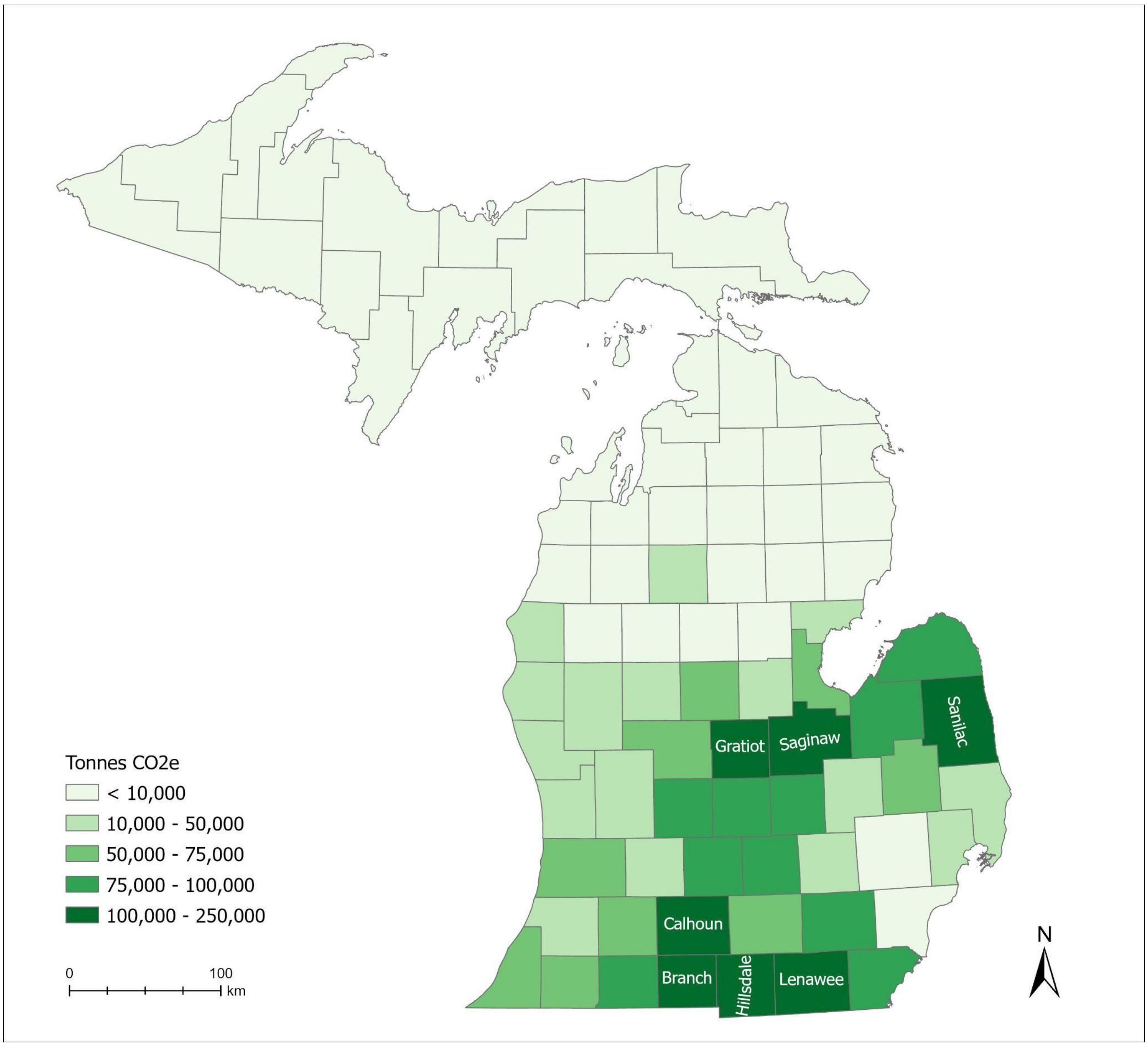

Figure 11: *Sequestration potential ranges greatly with the southern half of the state having more potential than the northern areas and the upper peninsula.*

From our analysis several trends become apparent. The northern part of the state, where little corn and soy is grown, tend to have lower sequestration rates for cover crop practices in both the irrigated and non-irrigated scenarios compared to the southern part of the state which is more heavily cultivated with these crops. However, high sequestration rates do not necessarily translate to overall high levels of sequestration potential. Hillsdale and Lenawee county both have the highest rates for sequestration and the highest potential, but the other top three counties for sequestration potential of Sanilac, Gratiot and Saginaw have a lower sequestration coefficient. In these counties, the acreage under cultivation and cover crop uptake influence the potential. Sanilac has great potential due to being the county with the highest acreage under cultivation (501,716 acres) and low uptake in cover cropping, at an approximate rate of 1 percent as of 2017. Gratiot and Saginaw similarly have some of the highest overall acreages in the state; while the percentage of cover cropping is higher in these states (both are above the 25th percentile) the two counties still have approximately 5 percent of land in cover crops, allowing for much potential to develop offsets in these regions. In short, high sequestration potential comes from some combination of high sequestration coefficient, low cover crop uptake and high corn-soy acreages.

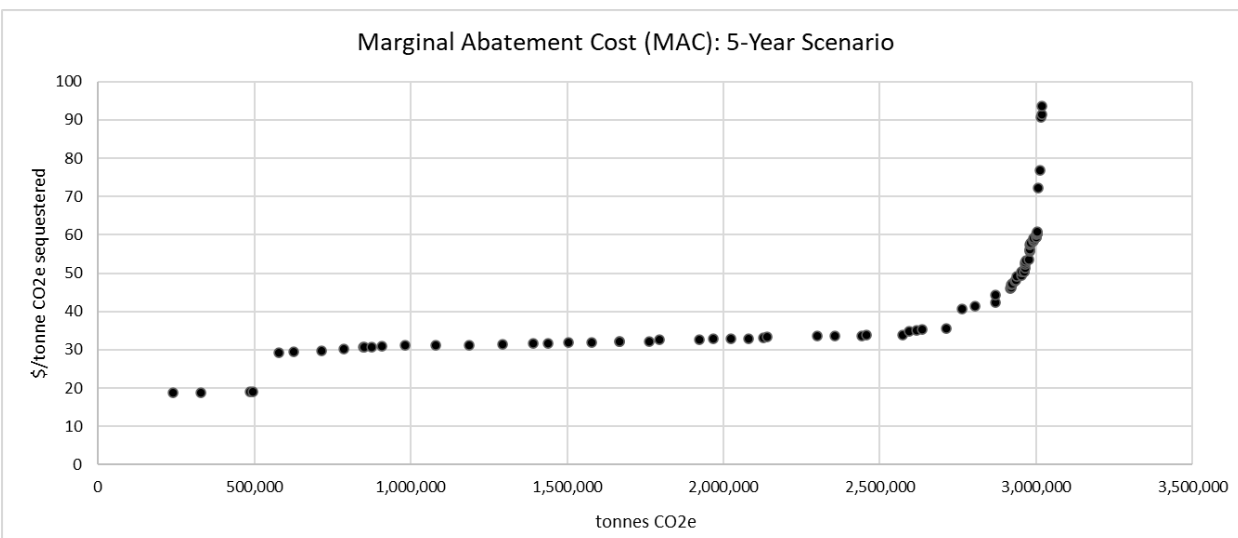

Figure 12 : *Estimated marginal abatement cost by county for the state of Michigan.*

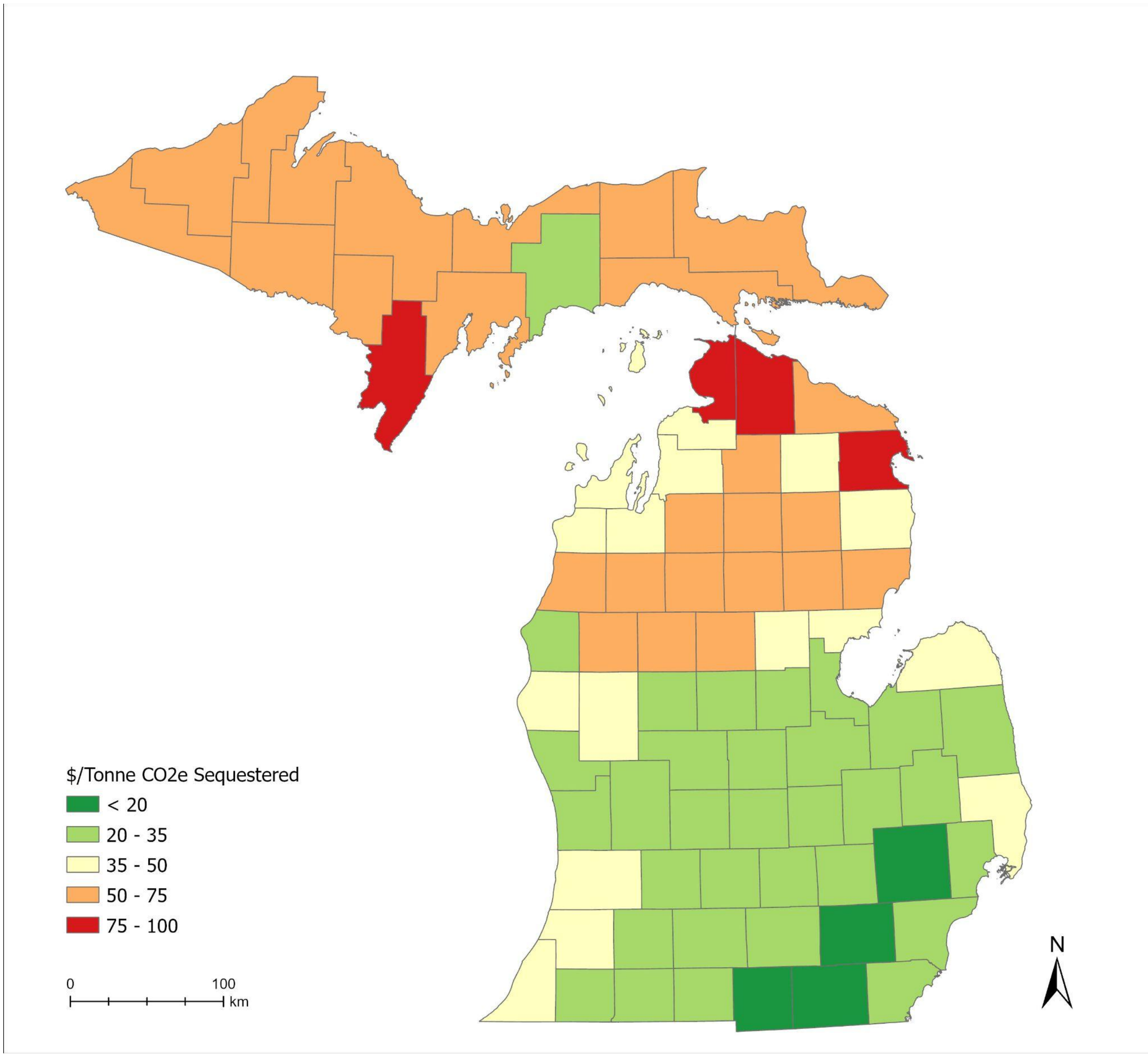

Figure 13: *The costs for cover crops range from less than $20 per tonne in a select few counties down state to $75-$100 in counties in a few counties in the northern parts of the state. Many counties fall between $20-35 per tonne.*

In Figure 13, we can see that the estimated cost of CO_2e sequestration ranges from approximately $18.50 -$93 dollars. The four counties with the lowest cost have sequestration costs below $19 per tonne of CO_2e; then there is a nearly $10 price jump to the next lowest cost counties. Comparing Figure 11 with Figure 13 suggests that Hillsdale and Lenawee may provide the greatest opportunities in the state for developing agricultural carbon offsets. These two counties fall below $19 per tonne of CO_2e as well as have some of the greatest potential for sequestration, with Lenawee sequestering 239,328 tonnes and Hillsdale sequestering 159,422 tonnes over a 5-year-period.

Discussion

Given the current market for agricultural offsets, Michigan offsets, particularly in lower cost counties, have some viability. The average cost of offsets in the United States was $15.5 in 2019 (Donfrio et al 2021), which is lower than the price of all offsets modeled here. However, the agriculture carbon offset market is still in its infancy, and some developers are naming higher price ranges for these offsets. For instance, Indigo Agriculture offers a rate of $20 per tonne for a five year contract and Land O' Lakes offers $25 per tonne. These prices exceed the estimated costs of implementing cover crops in the four lowest cost counties.

Many discussions around the development of agricultural carbon offsets centered on combining these market based incentives with federal policies that already exist to support farmers, such as the Environmental Quality Incentives Program (EQIP) run through the USDA's NRCS. EQIP offers farmers in Midwestern states around $50 per acre for implementing cover cropping (*Cover Crop Economics: Opportunities to Improve Your Bottom Line in Row Crops*, 2019, p. 7). Given the varying sequestration rates across the state of Michigan, this translates into an additional $2.5-$10.5 per tonne of CO_2e sequestered. The top performing counties for cost and sequestration potential have some of the highest sequestration coefficients (see Figure 14), meaning that combined with EQIP incentives, these counties have even lower costs, dipping below $10 per tonne. As illustrated in the maps below, many counties have a moderate sequestration coefficient between .11 and .13; these rates translate to incentives of $5.50 to $6.50 per tonne. Thus, when combined with these incentives, implementing cover crops as carbon offsets in counties where costs hover around $30 per tonne becomes viable given the current market conditions.

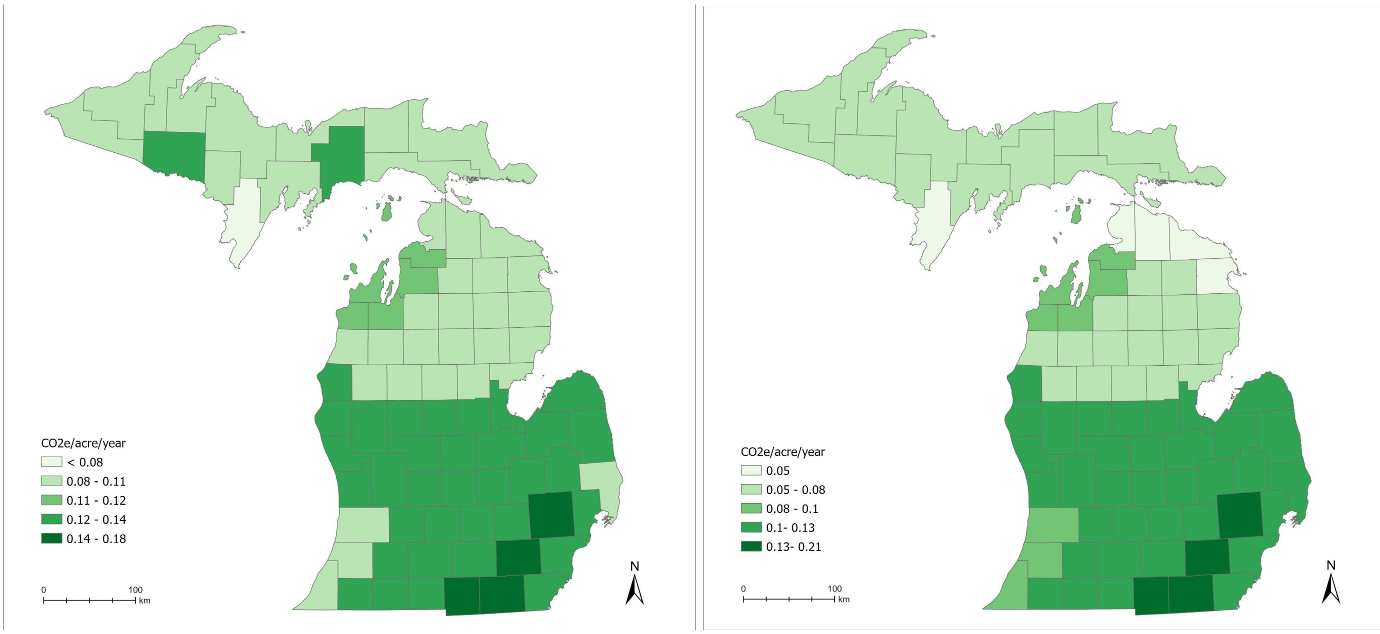

Figure 14: Sequestration rates for likely non-legume cover crop implementation on row crops such as corn and soy. Non irrigated croplands tend (right) to have a greater range of sequestration rates than irrigated lands (left). Map is based on rates developed through the USDA COMET-Planner.

Outside of current markets for carbon offsets, the implementation of cover crops makes sense given the costs of climate change. As noted earlier, new EPA estimates for the social cost of carbon are around 190 dollars per tonne of CO_2e, which is over double our highest cost estimates for implementing cover crops throughout the state of Michigan. Given the impacts of increasing CO_2 and other greenhouse gasses in the atmosphere, increasing cover crops throughout the state are cost effective ways to contribute to the mitigation of climate change. Thus policies like the Inflation Reduction Action and the Michigan Healthy Climate Plan should focus on incentivizing cover crops given their sequestration potential as well as the array of other co-benefits (detailed below) that they provide.

Our study has several limitations. Many farmers rotate between corn and soybeans, meaning that cover crops would fall between a season of corn and a season of soy. Given the different characteristics of these crops, it is possible that sequestration rates and costs could differ in these agricultural systems opposed to systems that were strictly one crop or the other. In addition, estimates of land eligible for cover crops may be biased; the 2017 census does not differentiate between harvestable land and pasture land, so estimates for cover cropping rates for harvestable land, or the type of land dedicated to corn and soy, may be skewed. Furthermore, our calculations of costs also had several assumptions that may or may not mimic actual farming conditions. While seeds for cover crops were included in costs, changes in labor or fuel costs were not included. Such limitations provide fodder for further studies on the potential of cover crops to be utilized as carbon offsets in the state.

Co-Benefits

Background

While the carbon markets will be accounting for the carbon sequestration performed by the various agricultural practices, these same practices also have the potential to provide a wide range of other benefits.

Numerous studies have quantitatively analyzed the multitude of co-benefits of planting cover crops. A cover crop consists of “any crop grown to cover the soil and may be incorporated into the soil later for enrichment” (USDA, 2023). The environmental co-benefits of cover crops include, weed growth suppression, increasing cropland diversity, reducing disease and insect pest harm, reducing soil erosion and associated water sediment and nutrient pollution, reducing fertilizer runoff and nitrogen leaching, increasing soil porosity, leading to better water infiltration.

Impacts of Climate Change on Agriculture in the Midwest

Before getting into the benefits of cover crops, it is useful to know about the impacts of climate change and how these new agricultural practices could help mitigate negative effects. The Midwest is a very diverse region, but one thing it all has in common is the large presence of agriculture. Understanding the impact that climate change will have on midwestern agriculture is also relevant to the use of agricultural and other nature based solutions. The National Climate Assessment projects that “mid-century yields of commodity crops show declines of 5% to over 25% below extrapolated trends broadly across the region for corn (also known as maize) and more than 25% for soybeans in the southern half of the region, with possible increases in yield in the northern half of the region” (Angel et al., 2020, p. 882) If there are significant declines in agricultural production in the region, then more land may be needed to meet food production needs, therefore there will be less land available for conversion into forests or other land use types for carbon sequestration. The use of cover crops and other regenerative forms of agriculture may increase resiliency against the effects of climate change.

Cover Crop Co-benefits

A key text for understanding the potential of nature-based solutions in the United States also provides a great supplemental table (see appendix) of the environmental co-benefits of the highest potential solutions. This table, put together by Fargione et al. may be referenced to identify the types of additional environmental services that nature based offset projects provide. As cover-cropping has been determined as one of the best options for carbon sequestration in the Michigan context, we will briefly go into a qualitative analysis of the co-benefits of cover cropping. However, the whole list of co-benefits for the major nature based solutions in the United States has been included in the appendix for reference.

Soil Erosion Prevention

Cover crops used during the late fall and winter fallow seasons can significantly reduce soil erosion and loss from agricultural fields by protecting the soil from wind and rain, establishing roots for soil to bind to, and improving water infiltration and reducing surface runoff (Clark, 2015). Non-legume cover crops have been shown to reduce soil loss by 31% to 100%, while legume cover crops have the potential to reduce soil loss between 38% and 69% compared to agricultural plots with no cover crops (Clark, 2015). Soil loss reduces agricultural productivity due to losses in soil that can hold water, nutrients, and organic matter (Chen et al, 2022, p. 1). As climate change will lead to more severe weather, such as droughts and heavy storms in the midwest, the implementation of cover crops has the capacity to aid in anchoring soil and reduce erosion accompanied by heavy surface runoff.

Water Filtration/Flood Control

Introduction of cover crops to an agricultural system has the potential to help off-site environmental services such as water filtration and reducing flooding. Cover crops and their root systems increase the soil's ability to absorb water through breaking up compacted soil and increasing soil porosity. This "provides a means to maximize effective rainfall and recharge of groundwater as well as reduce risks of floods, due to improved water infiltration" (Derpsch et al, 2010, p. 19). Using cover crops, along with a movement away from performing tilling-based agriculture can allow for fields to more effectively use and store rainwater, thereby reducing needs for irrigation all the while reducing runoff into nearby streams and rivers leading to increased flood risk.

Forestry Co-benefits

Other than trees' ability to sequester carbon into its organic structures and the soil, trees also provide a number of other valuable environmental services.

Social Benefits

Forests provide many opportunities for community engagement and recreational uses that often get overlooked when dealing with co-benefits of forest carbon projects. Firstly, Michigan forests provide the state with over 100,000 jobs and $20 billion dollars in economic impact (The Nature Conservancy Michigan, 2021). Additionally, reforestation projects can create opportunities for the local community to be involved in the planting process and nurturing of the growing forest, which can be an educational and community building experience for local residents. Lastly, forests are valued for recreation activities throughout the state, such as hiking and camping, that make it easy for anyone to enjoy the pure Michigan outdoors.

Absorption of Air Pollution

Trees have been shown to be able to absorb chemical pollutants from the air into their leaf structures. The main pollutants taken up by trees include nitrogen dioxide (NO_2), ozone (O_3), particulate matter 2.5 ($PM_{2.5}$), and sulfur dioxide (SO_2). A study published in 2014 estimated that pollution removal from trees and forests in the conterminous United States was 17.4 million tons with a human health value of $6.8 billion (Nowak et al, 2014, p. 123). While these findings are significant, the authors also note that, "96.3 percent of pollution removal from trees occurred on rural land" and that, "the health effects and values derived from pollution removal are concentrated in urban areas with 68.1 percent of the $6.8 billion value occurring with urban lands" (Nowak et al., 2014, p. 124). Therefore, trees in urban areas are going to have a much greater impact on pollution absorption, just from being closer to the abundance of local air pollution and higher human populations.

Biodiversity and Wildlife Corridors

The conversion of land from forest and prairies to pasture and agricultural lands has stripped the state of Michigan of a significant amount of biodiversity and habitat, through which species can move and migrate. While about 53% of the state is forested, this is still a large reduction from the 95% of the state forest coverage before Euro-American settlement (Cook, 2019). Deforestation of Michigan lands not only reduces carbon sequestration, but it also reduces habitat for the many species that call Michigan forests home.

The large areas of land transformed into monoculture fields and development of cities and roadways throughout the state has also led to fragmentation of crucial forest habitats. The presence of busy human landscapes can be a deterrent to wildlife's ability to migrate as needed. Large-scale agriculture and the disruptions of human settlements have created smaller pockets of natural forest habitat, which puts micro-populations at greater risk for isolation and local extinctions (Perfecto & Vandermeer, 2010). Therefore, reforestation and afforestation can play an important role in preserving biodiversity and conserving healthy wildlife populations throughout the state. In other words, “restoration plantings are a means to enhance biodiversity conservation in fragmented agricultural landscapes to form corridors and networks to link remnants of high conservation value” (Harrison, Wardell-Johnson, & McAlpine, 2003, p. 68).

Hydrological Services and Runoff Control

Planting of trees also has the ability to regulate local water cycles. Compared to the land uses that reforestation will replace, forests have a much greater positive impact on water quantity and quality. Forests aid in controlling water flows in regions after storms by “promoting infiltration, increasing soil moisture content and groundwater recharge, contributing to the gradual release of water” (Carvalho-Santos, Honrado, & Hein, 2014, p. 69). In comparison to grazing lands or agricultural fields, forests will improve water availability by increasing rainwater infiltration into the soil instead of contributing to runoff. That avoided runoff and erosion potential also contributes to healthier streams and watersheds due to holding soil in place that would have otherwise leaked into streams, causing sedimentation problems. These improvements can be valued for their impacts on stream quality, as well as reducing damages to any potential hydropower stations in the state of Michigan, as sedimentation is a common source of damage to dams and can reduce their electricity generation potential.

Ethical Considerations

Just like any other decarbonization strategy, the use of nature-based solutions is not free from potential environmental and social justice issues. These may include the ethics of using offsets to decarbonize rather than reducing emissions from operations, indigenous rights, and issues surrounding the accuracy of carbon accounting for nature-based solutions.

Ethics of Offsets

The choice to use nature-based solutions to offset any corporation or entity’s emissions is said to be ethical since greenhouse gas emissions become part of a global system, therefore, removing one ton of GHG from the atmosphere in one location is equal to abating one ton of emissions anywhere. Nature-based solutions can offer cost-effective ways to sequester significant amounts of greenhouse gasses from the atmosphere. While this is true, there are a few critiques that are common when it comes to using offsets.

One of the main questions concerning nature-based offsets is whether they are truly helping to speed up decarbonization or is the reliance on offsets allowing polluting industries to continue to emit greenhouse gasses into the atmosphere. In other words, offsets need to be taking greenhouse gasses out of the atmosphere, while at the same time not in any way limiting an industry's effort to decarbonize their own operations. Investing in carbon offsets should not in any way conflict with investments in carbon emission reductions. Offsets should not take away funding of internal decarbonization efforts.

As Michigan is home to a number of indigenous communities, it is crucial to recognize their lands, rights, and viewpoints on the use of carbon offsets. On a positive note, if nature-based solutions are developed on tribal lands, the financial benefits from the carbon credits can help low-income indigenous communities. The program director for the National Indian Carbon Coalition stated that, "Carbon markets are not the final solution, but at least they give tribes opportunities to develop additional practices and protect and preserve their natural resources" (Pember, 2021).

On the other hand carbon markets are seen by many indigenous communities as false solutions to climate change, that allow polluters to continue to pollute the Earth. In a report authored by the Climate Justice Alliance and the Indigenous Environmental Network, they write that, "Carbon pricing, including carbon trading, carbon taxes and carbon offsets, are false solutions to climate change that do NOT keep fossil fuels in the ground" (Gilbertson, 2017, p. 4). They go on to say that, "Carbon trading, carbon offsets and REDD+ are fraudulent climate mitigation mechanisms that in fact help corporations and governments keep extracting and burning fossil fuels" (Gilbertson, 2017, p. 4). While using nature-based solutions to reduce carbon emissions may have beneficial results and good intentions, not every community will agree with using markets to mediate a healthier relationship with our planet.

Leakage

One of the largest ethical/practical issues with nature based carbon offsets is the problem of emissions leakage. Leakage in an offset scenario can be defined as, "when some effects of the intervention fall outside the offset developer's accounting boundary (e.g., an action causing emissions reductions in one place may also cause increases elsewhere) (Filewood and McCarney, 2023, p. 2). Leakage has been a known issue for decades in carbon markets and while there have been attempts at better accounting for these emission displacements, the carbon accounting still remains flawed. Under-accounting of carbon project leakage results in projects and their owners getting credited with more carbon sequestration than is actually occurring. For example, a study from the University of California Berkeley stated that, "Analysis of projects generating 80% of total offset credits issued by the California Air Resources Board's (ARB) U.S. Forest offset protocol finds that 82% of these credits likely do not represent true emissions reductions due to the protocol's use of lenient leakage accounting methods". The impact of this is significant as the overcrediting in those projects "equals approximately 80 million tons of CO_2, which is one third of the total expected effect of California's cap-and-trade program during 2021 to 2030" (Haya, 2019, p. 1). Leakage, therefore, must not be overlooked when analyzing the true impact of nature-based offsets.

While the problem of leakage is embedded in the larger carbon market and therefore participants in carbon offsets have little power in preventing leakage, there are steps that anyone involved in offsets can take throughout the process. Firstly, offsets that minimize reduction in supply of the resource or product in question should be thoroughly analyzed or avoided (Filewod & McCarney, 2023, p. 9). Protecting a forest from getting cut down, or converting agricultural land to other higher carbon states may reduce supply of forest products or food production. If the demand for those products has not decreased, the decrease in supply is likely to create leakage, as the market will lead to increased deforestation or conversion to agriculture elsewhere. Additionally, nature-based offset projects should use conservative leakage estimates to ensure the credibility of the offset project (Filewod & McCarney, 2023, p. 11). Using higher estimates of leakage deduction rates in determining net carbon sequestration achieved in offsets, may reduce the attractiveness of many projects, but will produce more credible offsets that meet the criteria of additionality.

Future Considerations

Michigan Wetland Potential for Carbon Offsets

The MI Healthy Climate states that, "to drive decarbonization and sequester carbon in Michigan's natural and working lands sector, it will be crucial to protect and conserve Michigan's natural resources and support innovative solutions in agriculture" (p.47). For wetlands in particular they prioritize efforts to "protect and restore existing wetlands and waterways and create new wetlands where appropriate" (p.47). The first part of that sentence on protecting and restoring existing wetlands and waterways is most relevant to the state of Michigan, as creating new wetlands, in a carbon context, will not provide net benefits for hundreds of years.

A large global study of wetlands and their climate change mitigation potential found that restoring or recreating inland wetlands are not suitable for carbon offset markets due to their long switchover time. Switchover time "tells when exactly the ecosystem will have a net cooling effect" (Taillardat, 2020, p. 7). Restoration of wetlands significantly reduces CO2 emissions and over time is a great source for carbon sequestration in its soils. However, the inundation of lands with organic materials leads to respiration and decay of organic matter to produce methane emissions that, for decades or even centuries, will outweigh the climate benefits from carbon dioxide sequestration. The figure shown below depicts this fact that rewetted inland wetlands will have a net warming effect in most scenarios for decades to a few centuries after the wetland has been restored. The study's overall meta-analysis found the median switchover time for inland wetlands was 263 +/- 591 years, while only 8.5 +/-8.5 years for coastal wetlands (Taillardat, 2020, p. 10).

While it is true that wetlands are a very large carbon sink, the biogeochemical processes for inland wetlands lead to rewetted inland wetlands to be a carbon source on the decadal time scale. Due to the carbon market's need for short term carbon sequestration, restoration of inland wetlands should not be considered for potential carbon offsets. Therefore, the conservation of intact inland wetlands in the state of Michigan should be one of the top priorities instead of restoring the state's wetlands.

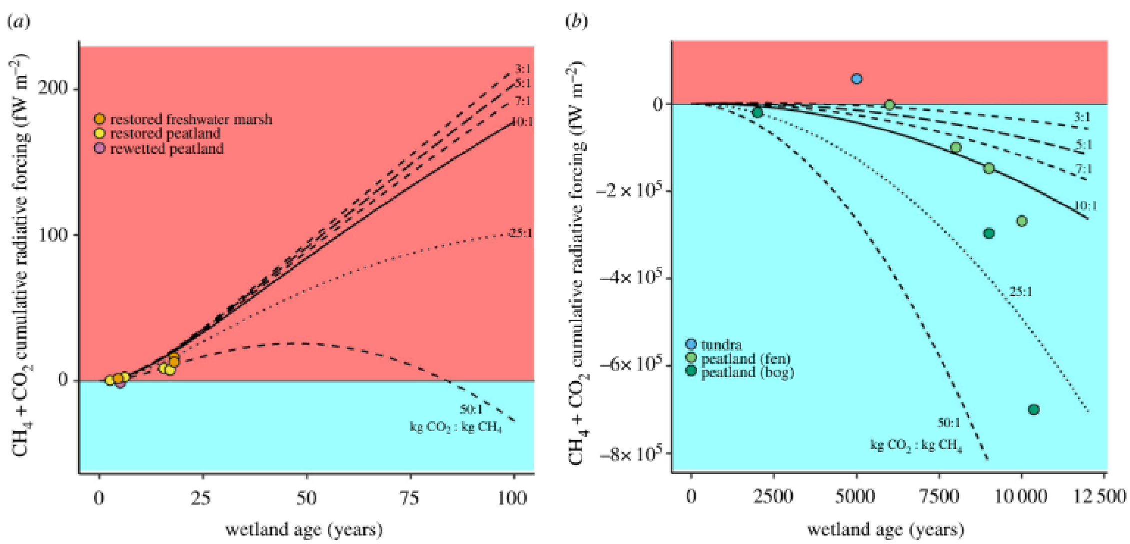

Figure 15: Radiative effects of wetlands & restored wetlands over a time-scale of 0 to 100 years. Reproduced from Taillardat et al, 2020, p. 6.

Biochar Potential for Carbon Offsets

The large-scale use of biochar has also been investigated as a potential source of substantial carbon sequestration in agricultural uses. Biochar is a, "stable solid, rich in carbon that is made from organic waste material or biomass that is partially combusted in the presence of limited oxygen" (USDA Northwest Climate Hub). The benefits of biochar in agricultural uses include "improving soil health, raising soil pH, remediating polluted soils, sequestering carbon, lowering greenhouse gas emissions, and improving soil moisture" (USDA Northwest Climate Hub).

Although numerous studies point out the carbon sequestration potential of biochar as well as its many co-benefits, costs prohibit biochar from being used at a commercial agricultural scale. A 2014 cost-benefit analysis of agricultural uses of biochar found that to be competitive, there would need to be a carbon price of at least 50 USD (Dickenson et al., 2014, p. 862). Currently there are not enough large scale producers in the midwest to allow for effective implementation of agricultural scale biochar to make for good nature based carbon offsets in the US. As of now, it is more cost effective to invest in biochar in the Global South, versus the United States, due to lower costs of producing large amounts of biochar (Dickenson et al., 2014, p. 862).

Given the high costs for large scale biochar use for agriculture, it would be recommended to remain aware of the biochar market for future potential. Also, it would be important to keep up to date on biochar with changing economic or political conditions, such as the addition of a national carbon price. There are about 69 countries as of 2021 that have some form of national carbon price ranging from $1 to $139 per metric ton (Doniger, 2021). The Biden administration has put in place a price of carbon of $51/ton, that would make it more feasible to do higher cost carbon abatement activities ((Eilperin & Dennis, 2021) .

The biochar market for large scale agriculture is in its nascent stage. With the potential that biochar usage in agriculture has on carbon and other co-benefits, the biochar market should be monitored for future use as carbon offset possibilities.

Additional Considerations

There are potential future opportunities and considerations DTE should consider when thinking about nature-based solutions within the state of Michigan. The first consideration is an analysis and model based on other offset types outside of forestry and agriculture. More specifically, developing models centered around biochar, avoided wetland conversion and grasslands may be of value for DTE if they choose to pursue offset types within these project categories. Another area that may be of value to evaluate is a more in depth analysis of the climate, market and policy implications of nature-based solutions. For example, including a qualitative analysis of the implications of recently introduced legislation such as the Inflation Reduction Act, as well as the Michigan Healthy Climate Plan would be useful in understanding the interaction between policy and offsets in the future. Lastly, another analysis that would be useful for DTE in the context of nature based solutions within the state would be the development of a leakage risk assessment. As offsets with high environmental integrity were flagged as an important priority for DTE, overlaying the forestry and agriculture models with risks for leakage would be an additional insight of value as DTE looks to source projects. Although our team did not include these considerations in the scope of analysis, these would be valuable areas for other potential teams to explore in the future.

Conclusion

Our study uses a combination of geospatial and ecosystem valuation methodologies to analyze the sequestration potential and costs of nature based carbon offsets in the state of Michigan. We developed a spatially fine grained analysis of reforestation potential and costs that account for variation at the intracounty level. In addition, we created a model for using cover crops as an offset on corn and soybean fields throughout that state, which accounts for characteristics specific to the offset market and local farming practices. In both cases, we estimate that these offsets are lower than the social costs of carbon. In addition, both types of offsets are economically competitive in the current offset market, under certain conditions.

Not included in these estimates of economic competitiveness are the co-benefits produced through these nature-based climate solutions. This study offers an overview of the key co-benefits for both reforestation and cover crop applications. These include benefits such as improved soil quality for cover cropping or added recreation for reforestation provided by these offset practices. Such co-benefits make offsets not only attractive to stakeholders but also competitive in the offset market.

In our benchmarking analysis, we rate six different offset markets for their potential to meet the needs of our client DTE. While our tool is interactive and could be changed depending on priorities, our current ratings suggest that American Carbon Registry offers the best value for a high quality offset. Therefore we recommended the development of reforestation offsets in the state of Michigan through using American Carbon Registry. However, as this registry does not currently have protocols for cover crop offsets, we recommend that cover crop offsets should be pursued through either Verra, which is currently reviewing protocols for certifying cover crops, or the Climate Action Reserve, the only major voluntary market that includes cover crop offsets at this time.

Finally, our analysis suggests that due to geographic differences, the development of cover crops and reforestation are not mutually exclusive. We find that cost-effective areas for reforestation carbon offsets exist in the northern parts of Michigan, while areas deemed cost-effective for cover cropping are in the southern part of the state. This suggests that a combined approach that uses both offsetting mechanisms in tandem can sequester the most carbon at the lowest cost. Ultimately, we hope that these findings can serve as a reference for DTE and other Michigan companies and organizations seeking to reduce their emissions and meet their carbon neutrality goals.

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Appendix

Environmental co-benefits of nature-based solutions in the United States. Reproduced from Fargione et al., 2018.

Pathway	Air (filtration)	Biodiversity (alpha, beta, gamma)	Soil (enrichment)	Water (filtration, flood control)
Forests				
Reforestation	Ozone abatement benefits of reforestation (*101*). Multiple modeling studies describe health benefits of air filtration by forests (*183*, *339*).	Tree plantings can create wildlife corridors and buffer areas that enhance biological conservation (*340*).	Measured increase in soil fauna in reforested sites. During drought conditions earthworms only survived in reforested areas (*341*).	Improved availability of water for crop irrigation, drought mitigation; avoided sedimentation and water regulation for hydroelectric dams (*342*).
Natural Forest Management		"Species richness of invertebrates, amphibians, and mammals decreases as logging intensity increases" (*343*).	Timber harvesting that removes large amounts of woody debris reduces soil biological and physical properties thereby reducing health and productivity (*344*).	Harvesting that removes large proportions of biomass increases water flows and flooding thereby altering freshwater ecosystem integrity (*345*).
Fire Management	"Possibility of small increases in mortality due to abrupt and dramatic increases in particulate matter concentrations from wildfire smoke" (*346*).	Fire management that mimics natural historic fire regimes can improve forest biodiversity (*347*).	Forests that survive fires (i.e. reduced catastrophic wild fires) contain more organic matter, improved soil properties, and lower recovery times enhance water infiltration and retention (*132*).	Increased runoff associated with severe forest fires due to eliminating the water holding capacity of the near surface organic layer and surface vegetation (*132*).
Avoided Forest Conversion	Ozone abatement benefits of reforestation (*101*). Multiple modeling studies describe health benefits of air filtration by forests (*183*, *339*).	"Results indicate the irreplaceable value of continuous primary forests for conserving biodiversity" (*348*).	Water retention and flow regulation (*346*). Maintains soil biological and physical properties ensuring health and productivity of forests (*344*).	Improved availability of water for crop irrigation, drought mitigation; avoided sedimentation and water regulation for hydroelectric dams (*342*).
Urban Reforestation	Pollutant removal including O3, SO2, NO2, CO, and particulate matter (*349*, *350*).	Researchers found that "urban green space with natural structures can maintain high ecological diversity" of bird species (*351*).		Urban forests can attenuate flooding for extreme weather events by storing water and limiting runoff (*352*).

Pathway	Air (filtration)	Biodiversity (alpha, beta, gamma)	Soil (enrichment)	Water (filtration, flood control)
Improved Plantations		Forest plantations that consider community type such as polycultures over monocultures, native over exotics, disturbance pattern replication, longer rotations, and early thinning can enhance biodiversity (*353*).		
Agriculture and Grasslands				
Avoided Grassland Conversion	Cropland causes air quality issues due to ammonia and particulates that have significant health impacts (*260*, *261*).	Important habitat for nesting and foraging birds (*354*).	Perennial grasses have little soil and nutrient loss compared to cropland (*355*, *356*).	Permanent grasslands provide "biological flood control" and maintain ecosystem water balance assuring adequate water resources (*357*).
Cover Crops			Reduces soil erosion and redistribution maintaining soil depth and water retention (*358*).	Reduces agricultural water demands with appropriate cover crops (*359*).
Biochar			The addition of biochar enhances soil quality and fertility in temperate regions (*360*).	
Alley Cropping	Tree planting helps capture airborne particles and pollutant gasses (*358*).	Agroforestry provides habitat for species and supports connectivity (*361*).	Decreased soil erosion (*362*).	Sediment retention and water recharge (*361*).
Cropland Nutrient Management	Nitrogen fertilization causes air quality issues due to ammonia and particulates, which are reduced at lower fertilization rates (*363*).	Increased indicators of stream health from macroinvertebrates (*364*) and leaf litter breakdown (*365*)		Reduced nitrate leaching (*366*) has benefits associated with improved drinking water quality, increased opportunities for recreation, and health benefits (*367*).
Improved Manure Management	Reduced N_2O and CH_4 emissions from manure management (*368*).	Hypoxic conditions related to manure runoff from agriculture causes attributed to Gulf of Mexico "dead zone" (*369*).	Manure management increase soil nutrients (*368*).	Proper management and timing of the use of manure as a soil amendment limit the chances of increased Nitrogen and

Pathway	Air (filtration)	Biodiversity (alpha, beta, gamma)	Soil (enrichment)	Water (filtration, flood control)
				Phosphorus runoff (*370*).
Windbreaks	Tree planting helps capture airborne particles and pollutant gasses (*358*).	Agroforestry provides habitat for species and supports connectivity (*361*).	Decreased soil erosion (*362*).	Erosion control and water recharge (*361*).
Grazing Optimization		A gradient of intensive to extensively grazed pastures reduces overall disturbance to plant-insect interactions (*371*).	Over grazing can reduce the soils ability to trap contaminants and cause a release of these and other suspended sediments (*358*).	Nearly 70% of water use for cattle occurs during farm grazing, managed grazing practices can reduce water use on managed pastures (*372*).
Grassland Restoration	Cropland causes air quality issues due to ammonia and particulates that have significant health impacts (*258*, *259*).	Important habitat for nesting and foraging birds (*354*).	"Soil macroinvertebrates are important prey for breeding wading birds on lowland wet grassland" (*354*).	Permanent grasslands provide "biological flood control" and maintain ecosystem water balance assuring adequate water resources (*357*).
Legumes in Pastures		The presence of legumes in prairie leads to higher insect herbivore and insect predator diversity (*373*).	"Legumes provide other ecological services including improved soil structure, erosion protection and greater biological diversity" (*374*).	
Improved Rice Management				Alternating wet dry and midseason drainage of irrigated rice fields reduces water demands for agriculture (297). The use of gray water in agriculture can reduce gross water consumption (*375*).
Wetlands				
Tidal Wetlands Restoration		Maintains the provision of structure, nutrients and primary productivity and nurseries for commercial fish and shrimp (*321*, *376–378*).	Benefits of cross-system nutrient transfer to coral reefs, coastal protection, and water quality regulation (*379*).	Remove nutrients and sediments from estuarine waters (*380*).

Pathway	Air (filtration)	Biodiversity (alpha, beta, gamma)	Soil (enrichment)	Water (filtration, flood control)
Peatland Restoration	Exposure to pollutants from peat fires increases in the need for health services to treat lung and pulmonary disorders (*381*). Rewetting peatlands reduces fire risk (*382*).	Regeneration of peatlands re-establishes diverse communities (*383*).	Restoring degraded lands to high productivity depend on faunal species that help develop soil structure and fertility (*384*).	Removal of nutrients from surface and groundwaters and storm water remediation (*378*, *385*).
Avoided Seagrass Loss		Increases faunal species richness, abundance and diversity and serves as nurseries for commercially important fish and shrimps (*380*, *386*).	Wave attenuation protects shorelines from erosion (*380*).	Remove nutrients and sediments from marine waters (*380*).
Seagrass Restoration		"increases faunal species richness, abundance and diversity" and serves as nurseries for commercially important fish and shrimps (*386*).	Wave attenuation protects shorelines from erosion (*380*).	Remove nutrients and sediments from marine waters (*380*).