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Agricultural Carbon Markets: How Could They Work?

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Agricultural Carbon Markets: How Could They Work?

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Abstract

The resurgence of voluntary markets in which consumers can purchase carbon credits generated by agricultural carbon sequestration has brought up many questions for farmers looking to potentially enter the market. Past carbon markets, such as the Chicago Climate Exchange, ended when a recession hit, causing demand for credits to swiftly decline. How can modern voluntary markets face these challenges along with new ones and be successful? This research paper, completed as an undergraduate thesis project at the University of Nebraska-Lincoln, examines the economic and scientific factors behind soil carbon sequestration credits. An extended literature review combined with estimation of a supply curve and equilibrium price for the market are used to provide farmers and the public with information about expected sequestration rates and costs for regenerative agricultural practices. The science behind no-till and cover crop carbon sequestration is explained as well as the economics behind production of carbon offsets by farmers and demand from consumers. Using data values found in existing scientific literature, a theoretical market supply curve and equilibrium price are created that can be used as a basis for further research.

Key Terms: Carbon markets, soil carbon sequestration, no-till, cover crops, economics

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Introduction

Since the Earth was formed, its climate has varied drastically (Ghil 2002). Periods of warming and cooling have occurred as slow processes over millions of years, but within the last 150 years anthropogenic activity has resulted in a much faster warming than ever measured before (USGCRP 2017). Due to our reliance on fossil fuels and other carbon-intensive activities, Earth now has a "carbon budget" (Le Quere et al 2018) defined as the remaining amount of carbon dioxide our collective society can emit before a tipping point of 1.5°C warming. The lifespan of this budget is not long in comparison to the rate at which we are transitioning towards carbon neutrality, and any action we can take to extend the budget is critical to avoiding the worst effects of global climate change. Soil sequestration of organic carbon is one solution to drawing down levels of atmospheric carbon dioxide (Lal 2004) that has the potential to be greatly increased.

While some industrial sectors are focused on creating mechanical methods of capturing carbon from the air, a natural method already exists: plants. The global carbon cycle is repeated every year as plants start to grow in the spring and throughout the summer and then become dormant or die in the fall and winter (Post et al 1990). In order to grow, plants perform photosynthesis to store sugars and produce energy. One of the main inputs in this process is carbon dioxide, which the plants gather from the air. As most plants grow, the carbon that was stored as sugar is used to produce biomass, making up a majority of the plant's structures. Part of the biomass of the plant will be located under the soil in the form of stems or roots (Sokol et al 2018). When the plant eventually dies, the biomass in the soil is decomposed and turned into soil organic carbon (SOC). If the soil is not disturbed, this carbon will remain in the ground for hundreds of years before re-entering the atmospheric pool.

The study of soil sequestration to mitigate climate change is based on this concept. In the United States alone, over 897 million acres (about twice the area of Alaska) of land are farmed annually (USDA-NASS 2020), but only about 140 million of these acres are enrolled in federal farm conservation programs (USDA-NASS 2017). Regenerative agricultural practices such as no-till, cover crops, crop rotation, and limited application of chemical fertilizer are often a requirement of these programs and have the result of increasing soil carbon sequestration rates. While 140 million acres is a large area (about the size of New York and California combined) there still exists potential to store more carbon in our soils.

Besides carbon sequestration, there are many benefits to practicing regenerative agriculture, such as increased biodiversity, reduced runoff, minimized soil erosion, and improved ecosystem resilience (White 2020). There might also be costs, including potential initial costs such as the purchase of new equipment or greater time spent working (Manley et al 2005). A farmer's job includes risk assessment; they must use data and prior knowledge to make decisions for what and how much to plant, how much fertilizer to apply, how much to irrigate, etc. (Selvaraju 2012). For this reason, most farmers tend to prefer to use methods of farming that are familiar and reliable and are hesitant to switch to something new. Poor implementation of a new practice could result in a loss of income that the farmer and his or her family is counting on. Therefore, regenerative agricultural practices are often incentivized by the government to encourage farmers to adopt them. The results of these practices are a net benefit to society, so the government justifies the taxpayer expense.

Incentives do not always come from governments, however. Producers can be enticed to farm using carbon sequestering methods if they can accurately quantify and then sell the amount of carbon dioxide that has been sequestered as a carbon offset credit. In this way, the free market works to internalize a negative externality (carbon dioxide emissions) by making the externality a commodity that has value (Varadarajan 2020). Demand also must exist for the market to sustain itself. If there is great demand from consumers and businesses to offset carbon intensive activities such as flying in a plane, the price paid to farmers per ton of carbon dioxide sequestered will be higher and more producers will be likely to use sequestration techniques. Conversely, if demand is not high, prices will be low and a small number of farmers will put in the time and effort required to sequester carbon (Gale 1955).

If private enterprise can so easily provide a solution to the problem, why hasn't it? Voluntary carbon markets have existed and failed in the past, and some are still operating today. The United States' main carbon market, the Chicago Climate Exchange, failed in 2011 after collapsed demand (Sabbaghi and Sabbaghi, 2016) and other factors that will be discussed later. More recently, several private firms have begun to contract with farmers to sequester an agreed upon amount of carbon dioxide, then sell those carbon credits by the ton to consumers.

For a modern agricultural carbon market to work, we need to understand why past markets have failed and the dynamics of supply and demand for soil-sequestered carbon. This report and literature review will provide information on how current and future agricultural carbon markets can succeed and the tools necessary for fair, accurate, and effective transactions to take place in the market.

Key factors that need to be considered include the quality of carbon offsets and the equity issues surrounding climate change. An offset that only guarantees the sequestered carbon to remain in the soil for five years has lower quality than an offset that guarantees the sequestered carbon will remain in the soil for thirty years. The verification methods used to create carbon credits will also affect the quality. Verification sources that are widely accredited and standardized will produce higher quality offsets than verification sources that are proprietary to the voluntary market. Additionally, voluntary carbon markets have been criticized for not being effective and simply moving money around while not making any real long-term sequestrations (Climate Justice Alliance 2017). This notion may be due to issues with quality credits in past carbon markets, and will be addressed in this research.

The work for this research began with a single question: How can an agricultural carbon market work? After doing preliminary research on the subject, five additional questions were proposed to supplement the main question. Each of the sections in this literature review will be centered around answering one of the five supplementary questions. These supplementary questions are:

- Why have past agricultural carbon markets failed?
- What challenges do agricultural carbon markets face?
- How can an agricultural carbon market be sustained in the long term?
- Are agricultural carbon markets effective at sequestering carbon?
- Are agricultural carbon markets equitable?

Literature Review

When researching the subject of voluntary agricultural carbon markets, extensive popular and scientific literature is available. However, there are major differences between the relevancy and helpfulness of the information in each category. The existing scientific literature covers most of the aspects of historical carbon markets (the Clean Development Mechanism, Chicago Climate Exchange, and Emissions Trading System) but contains very little information on modern markets. Nori, Indigo Ag, Truterra, and other newer markets have started their programs all within the last year or two (with some yet to begin conducting transactions) so there has not been a lot of time for research on these markets to occur. Additionally, it will be several years before data regarding price and volume of credits traded has built up and can be studied empirically for trends. However, the research that has been done on the CDM, CCX, and ETS is extensive and useful for studying how voluntary carbon markets can succeed. Scientists have studied and written about the factors that caused each market to succeed and fail, and these publications are of immense value to anyone looking to learn from the mistakes and triumphs of these past markets.

On the other side, popular literature has become increasingly engrossed with the subject of agricultural carbon credits since the beginning of 2021. The change of Presidential administration spurred this interest as the Biden administration is determined to find economical solutions to climate change. They have tasked the US Department of Agriculture with implementing a way for farmers to achieve net-zero greenhouse gas emissions from agricultural operations, and USDA is reported to be looking into the idea of a carbon bank to assist farmers and the voluntary markets. However, many of the popular articles about the rise of voluntary markets and how American agriculture can play a part are written with considerable skepticism towards the idea. The shutdown of the Chicago Climate Exchange in 2010 is still fresh in the agriculture industry's mind, and they understandably do not want to waste effort on a repeat market that might end the same way. The industry is also resistant to government intervention, so the idea of a federally run carbon bank is unappealing to some.

These perceptions are important to understanding agricultural carbon sequestration as popular articles written by agricultural publications are one of the main sources of information for agricultural producers. Public university extension services have also been providing information online about signing carbon credit production contracts with market firms, which is a vital source in the absence of scientific literature.

Answered Questions

Over a decade has passed since the Chicago Climate Exchange ceased carbon credit trading operations. In this time researchers have dug into the benefit to consumers (Gans and Hintermann 2013; Boulatoff et al 2013), the relationship between agricultural ecosystem services and marketability (Ribaudo et al 2010), the efficiency of information exchange and data sharing (Sabbaghi and Sabbaghi 2016), and additionality requirements (Kollmuss et al 2008). The CCX, along with the European Union's Emissions Trading System and the Kyoto Protocol's Clean Development Mechanism, has been covered extensively in the scientific literature. The information that is available is valuable to not only those who desire to run a voluntary carbon market but also potential producers in the market, consumers, banks, investors, and agricultural economists. While the Chicago Climate Exchange successfully traded hundreds of millions of credits over the course of its operation, it ultimately came to an end. More than a decade later, with the advantage of hindsight, multiple lessons can be learned from it that will provide for better markets in the future.

There also exists plenty of literature on the differences between voluntary carbon markets and other decarbonization mechanisms. An insightful paper by Jonathan D. Rubin explains how market forces automatically act to make the least cost emissions reductions first, leading to market efficiency (Rubin 1996). Scientists have also studied the relationship between cap and trade legislation and prices for carbon markets (Mizrach 2012) and the effectiveness of voluntary sequestration efforts with no government regulation (Yang 2006; Farleigh 2003). The existing literature covers the aspects of voluntary markets, cap and trade, and carbon taxes and is continuing to evolve as technology improves and policies are implemented.

Measurement of soil organic carbon (SOC) is vital to the functioning of any carbon sequestration activities, and the scientific literature that discusses accurate methods of measuring changes in SOC content is extensive. Scientists have written about the ability to measure SOC content directly (Yan et al 2011) and on a regional scale (Stevens et al 2010), and both will be used in modern carbon market systems. An article by Rattan Lal provides an in-depth look into the multiple factors that affect soil carbon content, including changes in management practices (Lal 2018). Uncertainty also exists in some methods of soil organic carbon content estimation (Ogle et al 2010), but the uncertainty can sometimes be accounted for in order to produce viable carbon credits anyway (Stockmann et al 2013). While measurement technologies and methods are continuously improving, soil carbon measurement is a subject that is pertinent to multiple fields, not just the voluntary carbon market. The literature will continue to evolve as well.

Gaps in the Literature

Few scientific articles have been published about the re-emergence of carbon markets within the past few years. Because these firms are so new, there has not been much literature written about them. Significant gaps exist around the levels of supply and demand for carbon offset credits in the present, which is pertinent information to the success of voluntary markets. Additionally, there is an aspect of competition that has not been present in historical carbon markets. Both producers and consumers of carbon offset credits have many choices on which market firm they want to sell to/buy from, which creates economic competition that has not been researched.

Modern data reporting technology is an area that is also lacking scientific literature. Most firms use similar but proprietary reporting technology, and it is of value to know how farmers use the software. Differences in ability to report information on the software are problems that would need to be addressed for the market to expand and provide all producers equal opportunity, but the potential differences cannot be dealt with if they are unknown. Also, the amount of data producers are required to report for different market firms is not public knowledge. If there were to be scientific or informative literature comparing the data requirements for each program producers would benefit from the additional information.

The final commonly overlooked issue regarding voluntary carbon markets is the equity associated with this strategy of decarbonization. In the world of carbon offsets, the term "equity" refers to ensuring groups who have been and will continue to be the most affected by climate change are supplied with resources that increase their resilience. A well-researched article titled *Carbon Pricing: Effectiveness and Equity* examines how the social cost of carbon relates to the price of carbon credits in modern markets (Boyce 2018), but other than this paper there is not much else. Equity is an important aspect of climate justice as the climate crisis affects everyone, and everyone deserves a chance to be part of the solution. Additional research on how the voluntary markets can be accessible to everyone would benefit policymakers and the firms running the trading platform by helping them make informed decisions on how best to ensure equity.

Summary

Climate change is a pressing issue that requires immediate action, and a carbon market predicated on regenerative agriculture is a potentially important solution. Information related to the factors of supply, demand, verification, and measurement of an agricultural carbon market is critical to the successful and long-term function of the market. The purpose of this research is to answer the research questions in greater detail. The findings of this research will be made public and aim to serve those who want to participate in or aid the market including farmers, agricultural commodity boards, government officials, and carbon offset consumers.

Methods

To adequately answer the proposed research questions, multiple methods are used in this research project. Because the scope and topic of the research are both broad, examining both scientific and economic factors through an analysis approach will provide a comprehensive look into the details of agricultural carbon markets.

Over the summer of 2021, an extended literature review was completed by doing research using scholarly databases and publicly available materials. It covered the history of carbon markets from the Kyoto Protocol's CDM in 1998 to the present state of recently developed private markets. The literature review also addressed problems modern markets face that they must overcome to be successful. When doing the research for the literature review, peer-reviewed journal articles were the primary source of information. These articles were accessed by using UNL research databases and specific search terms. However, a number of secondary "popular" articles were also used. This was important to the project as the information gained from non-scientific articles allowed for analysis of popular opinion on the subject and real interactions actors in the market have experienced.

There are not many comprehensive, updated summaries of how agricultural carbon markets work that relate economic principles to them, so this report was developed as a public source of information for potential market participants. In September of 2021, it was published on the UNL digital commons and can be accessed by anyone with an internet connection. The goal is for it to serve as a resource for people seeking more up to date information about carbon markets and carbon offsets as well as a collection of academic and popular resources for further exploration.

Excerpts from this report make up Chapter 1: The Past, Present, and Future of Voluntary Carbon Markets.

The second part of the research is focused on using existing scientific literature on the science of soil carbon sequestration to analyze the effectiveness of different practices. Switching from conventional till to no-till and planting cover crops are the two primary forms of carbon sequestration that will be studied in Chapter 2. Readers of this thesis will likely find specific expected values of soil carbon sequestration helpful, so these values will be included. Also included will be the costs associated with the changes in practice that a farmer can expect to incur.

The final section of this thesis involves using the average cost and sequestration data found from existing literature in Chapter 2 to create a theoretical supply curve for carbon credits. The economic concepts of willingness to pay and willingness to accept will be considered for carbon credits, and an equilibrium willingness to pay price will be incorporated into the supply curve graph to show the quantities and prices at which transactions might occur. While it might not be completely reflective of current market conditions, the graph will serve as an example framework for further research.

Chapter 1: The Past and Present of Voluntary Carbon Markets

What are agricultural carbon offset payment programs?

Many people have heard the term "goods" before, likely in reference to products or services in the marketplace. Not as many are familiar with the concept of an economic "bad"- the opposite of an economic good. While goods provide the consumer with utility in the form of greater satisfaction, economic bads detract from our utility and cause less satisfaction (Turvey 2000). As is well established by climate science, the release of carbon dioxide from anthropogenic activities is an economic bad (Li et al 2019). Additional carbon dioxide (a greenhouse gas) in our atmosphere causes more heat to be trapped on Earth, resulting in a myriad of negative effects for the global population (Tol 2009). Therefore, consumers who desire to lessen the effects of climate change value less atmospheric greenhouse gases. While consumers will pay to have a greater amount of goods, they will also pay to have a lesser amount of bads- think paying for a trash disposal service. The actions of a single individual are relatively insignificant, but the collective action resulting from a carbon market can potentially be enough to make a dent in the amount of carbon dioxide in our atmosphere. This concept is fundamental to the operation of carbon offset payment programs.

In a carbon market, consumers exchange money for the rights to claim a carbon offset, which is an agreed upon amount of carbon dioxide that is either not emitted where it otherwise would be or sequestered directly from the air into a non-atmospheric form (Lovell and Liverman 2010). A carbon offset is an example of a credence good, which is a good that gives the consumer satisfaction due to its qualities, even though the consumer cannot experience them. While the consumer's life is not directly made better by the transaction, they recognize the severity of the climate crisis and gain utility from the knowledge that they are decreasing the amount of carbon dioxide emitted. The consumer's money is transferred to a marketplace institution that facilitates transactions of carbon offsets between buyers and sellers, then passed on to the seller of the carbon offset. Many of the sellers in the carbon offset market are farmers who are actively sequestering carbon dioxide in their ground through regenerative farming practices (Giller et al 2021), and the payment they receive helps cover any costs associated with the change of farming method.

The institution that facilitates carbon offset transactions is important for two reasons. First, carbon dioxide offsets are dissimilar to the purchase of other products. The consumer does not receive a physical product as they would if they went to the store and bought something, and they also do not receive a service. Instead, they receive confirmation that a measured amount of carbon dioxide has been sequestered on their behalf (Liu et al 2015). For the confirmation to be legitimate, it must be verified. This requires accurate methods of measuring soil organic carbon (SOC), which will be discussed later in the literature review. A carbon market institution can standardize the verification and measurement methods, ensuring every carbon offset is equally valuable (Haya et al 2020).

Second, the market is more efficient when there is an entity that handles the transactions between buyers and sellers (usually these people are referred to as brokers). It would be inefficient for every buyer to individually contact a seller that they were interested in purchasing carbon credits from and arrange for their own measurement and verification costs (Bessy and Chauvin 2013). Some larger farming operations might have thousands of metric tons to sell and arranging sales that might be a few tons at a time would be both time consuming and expensive for the farm operation. Conversely, the consumer might desire to purchase more metric tons at once than any one producer could provide. For example, Microsoft has purchased 1.3 million metric tons of carbon dioxide emissions offsets in 2021 through the company TruTerra (Watson 2021). As there is not an agricultural operation producing anywhere near this amount, Microsoft would have had to expend time and money procuring smaller amounts of offsets. Without the intermediary, the volume of carbon offset transactions would decrease as the transaction cost would be higher, reducing quantity demanded.

Even though the product may be unlike those in a traditional market, carbon markets are still governed by the same economic principles of supply and demand. Given consumer demand exists for offsets and agricultural producers are willing to invest in producing them, as well as an entity to facilitate transactions, the result should be a net negative amount of atmospheric carbon. But how effective are agricultural carbon offset programs?

Are agricultural carbon markets effective?

When tackling an issue as large as climate change, no one solution will solve the problem. Rather, a combination of solutions involving decreasing the amount of carbon emissions now and sequestering atmospheric carbon to extend the carbon budget will be used. Frequently touted as a cost-effective solution (Osborne 2015), the commodification of carbon dioxide has potential to offset a substantial portion of global climate emissions. However, critics say that the market simply moves money around without keeping carbon dioxide out of the air (Gilbertson 2017). This section will explore the variables that determine how much carbon dioxide agricultural carbon markets sequester.

Voluntary vs Regulatory

Debate among economists and scientists about the way a carbon market should (or should not) be regulated has existed since their genesis. A regulatory carbon market arises when a governing body either imposes a tax on carbon emissions or imposes limits on carbon dioxide emissions (Schillie n.d.). If the regulations allow pollution permits to be tradable, polluters who face high pollution reduction costs will buy permits from polluters who face low pollution reduction costs. Prices for the permits are established based on the buyer's willingness to pay and the seller's pollution abatement costs. Like how cryptocurrencies derive their value based on a finite amount of the currency being available, each emissions credit has value because it gives its holder the ability to emit carbon dioxide when only a set amount can be emitted (Fang et al 2017).

The opposite of a regulatory approach to market governance is a voluntary one. In a voluntary carbon market, there is no emissions cap ((Schillie n.d.), so for the buyers each credit's value comes from consumer demand and the utility it can provide. Buyers in a voluntary carbon market might be motivated by wanting to claim low-carbon or carbon-free status. The market is also largely unregulated, resulting in a possible difference in standards. This type of market can cover multiple sectors of the economy since no regulation is involved targeting specific sectors. Any carbon offset or sequestration credit (both offset and credit refer to the same thing and can be used interchangeably) can be priced and sold in the carbon marketplace, no matter the industry it came from. One benefit of this type of market structure is that there is no cap to the amount of carbon dioxide that can be sequestered (Corbera et al 2009). If supply and demand push the equilibrium quantity above where the cap would be if the market were government regulated, the voluntary market is more successful than the regulated one at sequestering carbon.

Another advantage the voluntary market has is that it fosters innovation (Guigon 2010). In response to the questionable results of the Kyoto Protocol's Clean Development Mechanism (CDM), standards in the North American voluntary market were developed to determine how much carbon was being sequestered beyond normal rates- a concept known as additionality (Michaelowa et al 2019). Also, because there is less regulation and compliance guidelines, more entities are free to enter and exit the market. Regulated markets can sometimes have the unintended effect of keeping some producers out because they lack technical or financial capital (Guigon

2010). In a voluntary agricultural carbon market, any producer is free to participate if their carbon offsets meet the standard put forth by the market for a particular offset. This effect helps keep smaller producers on the same footing as the larger corporations.

In considering the potential effectiveness of a particular offset market, it is imperative that the perspective of the farmer-suppliers be considered as well as that of the buyers. An overwhelming majority of farmers prefer a voluntary approach to carbon markets over a regulatory one (Kitchens 2020; Center for Climate and Energy Solutions 2021; Schattenberg 2021). Reasons for this include a general dislike of government constraints that limit their ability to do what they think is best for their crop. In a voluntary market, farmers choose to participate in the marketplace and make changes in the way they farm, whereas regulatory market conditions might force them to make changes they don't want to. Carbon sequestration credit producers are also concerned about the increasing amount of market power wielded by agricultural product buyers and the possibility of losing market share to large companies. Voluntary markets allow small producers to participate in the same market as the corporations, whereas if a compliance market were to be put in place they might not be able to participate due to possible economies of scale in meeting regulatory requirements.

Overall, the existing literature shows that the benefits of regulatory and voluntary carbon markets are mixed. Voluntary markets may have a credibility problem. The lesser standards for offsets produce credits that won't last as long, and the variability in verification services reduces the amount of standardization. However, there is a downside to regulatory markets as well. Basic supply and demand show the same thing: when a tax or restriction is placed on the market, price increases and quantity demanded decreases, resulting in a deadweight loss and a less efficient market (Hausman 1981). There is not enough evidence to definitively say whether one type of market structure is better than the other, so the effectiveness of a carbon market will depend heavily on other factors.

Regional vs Global

The scope of agricultural carbon markets is another determinant of their efficacy. Regional markets have the potential to be specialized and better serve producers locally, but global markets give access to remote producers and people in places where a regional carbon market does not exist (Michaelowa 2011). Due to the scale at which global markets operate, they are less likely to be regulated as well. Perhaps the most well-known global carbon market is the Kyoto Protocol's Clean Development Mechanism (CDM) that allowed the trading of carbon credits internationally and aimed to promote sustainable development in rural communities. Unfortunately, the CDM failed to deliver on most of its promises (Subbarao and Lloyd 2011) and the legitimacy of its credits was called into question.

In a 2017 research paper, NYU Professor of Environmental Studies Jessica F. Green argues that linking regional carbon markets into a larger conglomerate ultimately makes them less effective. Green's reasoning is that the more governments there are trying to regulate a carbon market, the more volatile prices can be within the market (Green 2017). However, Green's discussion of linking carbon markets refers to compliance markets that arise from government regulations, not voluntary markets. She notes that if it were possible to create one central, global carbon bank the stability of the market would likely be enough to promote trade and expansion, but the difference in standards and currencies simply make the idea unattainable. Contrarily, in a 2010 research paper Fankhauser and Hepburn argue that the linking of carbon markets provides flexibility in the market, which helps to reduce compliance costs producers face. They also note that in a more traditional product market, the higher the number of buyers and sellers the greater the stability of the market (Fankhauser and Hepburn 2010) (Lanzi et al 2012). While the combining of regional markets for other products often produces favorable results, carbon credits are not like other products. As it stands right now, the existing literature is not clear on which geographic approach produces the most effective results for carbon sequestration.

Effectiveness of Agricultural Carbon Markets

In the existing literature surrounding meaningful carbon dioxide sequestration because of carbon market policies, scientists make cases for and against the practice. It is widely recognized as a cost-effective solution to the climate crisis (Boyce 2018) due to classic economic reasoning. When faced with a negative externality, consumers choose the cheapest way to internalize the externality, enabling society to efficiently allocate resources to the problem (Yin and Lawphongpanich 2006). This leads to "picking the low-hanging fruit" first and quickly decreasing atmospheric carbon dioxide in the most efficient way.

As discussed before, implementation of a compliance carbon market often leads to an increase in innovation in response. The United States' cap and trade system for sulfur dioxide emissions is a fitting example of this phenomenon. According to a research paper from 2000, this program caused rapid technological innovation to occur within the first 10 years of its use (Burtraw 2000), enabling power plants to cut back on sulfur dioxide emissions even more.
Data from the European Union's Emissions Trading Scheme (ETS) supports this concept further. The ETS is a compliance carbon offset market resulting from emissions caps on carbon dioxide.

It involves members of the European Union in a cap-and-trade system, and many of its carbon credits come from agriculture. After the commodification of carbon dioxide in the EU, patents regarding "low carbon technologies" increased (Calel and Dechezlepretre 2016). We could expect a similar jumpstart to U.S. funding and research if American carbon markets grew to a place of prominence in our agricultural and resource economies.

Carbon markets have another advantage over other types of emissions reduction policies. Anyone is welcome to participate in a carbon market, resulting in greater equity (Stavins 2008). Carbon taxes usually regulate large industrial centers and power plants, excluding individuals to some extent (although the tax might get passed on in some capacity to the consumer). However, in a carbon market any individual is free to offset his or her personal emissions directly through the purchase of carbon credits.

Most of the critical literature on voluntary carbon markets focuses on the fact that when implemented alone, they will not sequester enough atmospheric carbon to keep Earth's warming below a tipping point of 1.5°C (Kuhns and Shaw 2018). This is true, and the fact is climate change is a global problem with many necessary solutions. An agricultural carbon market will be most effective when used in conjunction with other forms of carbon dioxide emission reduction and sequestration. Carbon taxes and cap and trade are two other useful tools which will be discussed in the next section.

Other Methods of Reducing Emissions

<u>Carbon Tax</u>

A tax on carbon is one government way of dealing with carbon emissions directly. The economic reasoning supporting a carbon tax is that carbon dioxide is a pollutant that creates a decrease in social welfare, so raising the cost of emitting a metric ton of carbon should decrease the quantity that is emitted (Metcalf 2019). If a government is considering implementing a carbon tax, they commission research to find the optimal price of the tax so that an effective amount of carbon dioxide will not be emitted when it otherwise would be. Supporters of a carbon tax argue that the tax keeps fossil fuels in the ground, which is one of the most effective ways to minimize the release of carbon in the first place (Van der Ploeg and Withagen 2014). They also say it is the most cost effective at bringing down emissions levels (Lin and Li n.d.). Proposed ideas for the revenue generated from a carbon tax include reinvesting the funds into renewable energy research, a rebate to the American taxpayer, or a combination of both.

Any solution comes with drawbacks, however. One of the main criticisms of carbon taxes is that they unfairly distribute the tax burden over income levels (Williams III et al 2015). It is considered a regressive tax because low-income persons would pay a larger fraction of their income in the tax than would higher income persons. This decreases the tax burden for an individual the higher their income level is, and some economists claim that a carbon tax would have this effect. It may also be politically difficult to implement, depending on the public's perception of what will be done with the tax revenue (Gevrek and Uyduranoglu 2015). Still, these issues are ones that can be overcome for a carbon tax to be implemented and work alongside agricultural carbon markets synergistically.

Cap and Trade

Cap and trade is frequently mentioned in conjunction with carbon markets. The term is used to refer to when a government sets a limit on the amount of a pollutant that can be released over a set time period (the "cap") and then distributes emissions permits to firms in the affected industries (Stavins 2008). Each firm can then decide to either reduce their own emissions and sell their excess permits (if any) or continue to emit at the same level and buy permits from other firms to comply with the policy. This results in efficient use of resources by industry as the cheapest methods of reducing emissions are employed first (Chen et al 2020). Proponents of a cap and trade system argue it is beneficial for this reason as well as its ability to put a hard cap on the amount of annual emissions, providing a degree of certainty (Kaufman 2016).

Critics of cap and trade claim energy producers and other carbon intensive industries are too hard hit by the policy (Curtis 2014) and the technology for low carbon operations does not exist yet. However, this first criticism seems to be directed at the EPA's Nitrous NOx Budget Trading Program and not at any carbon cap and trade program. As shown by the effect of the U.S. government putting a cap on sulfur dioxide emissions, innovation flourishes in response to efforts to curb pollution. Others argue that there exists a "rebound effect" that limits the gains in emissions cuts received by increasing efficiency due to consumer behavior (Jarke-Neuert and Perino 2020). While there may be some drawbacks economically, multiple governments have employed cap and trade programs with success (Wood 2018), and again is a tool in the overall need to lower carbon emissions.

Summary

As discussed in the introduction, global climate change is too large a problem to require just one solution. Evidence from both voluntary and regulatory carbon market performance shows that they are effective at sequestering (in the case of agriculture) and keeping carbon dioxide from being released (in the form of offsets), while the polices of a carbon tax and cap and trade help by setting emissions caps and regulating heavy carbon industries. The degree to which each is employed around the world will vary by region, but all three are valid solutions to help stop anthropogenic climate change. A report by the World Resources Institute finds that as long as these policies are well designed, most critics' claims are no longer supported by evidence (Kaufman 2016). Several voluntary carbon markets have existed in the past or still exist today, and the next section will focus on the successes and failures of each.

History of Programs That Provide Carbon Offset Payments to Farmers

The concept of a carbon market that trades offsets generated by agriculture is not a novel one. Earlier markets, such as the Chicago Climate Exchange (CCX), linked large and small scale producers and consumers to trade 680 million metric ton credits throughout the course of its operation (CCX 2010). Even before the CCX was the Kyoto Protocol's Clean Development Mechanism, which was a compliance market created to encourage investment from "developed" countries into emissions offset projects in "developing" ones. Later, the European Emissions Trading System was founded and still trades credits today. What were the successes and failures that led these markets to where they are now?

The Chicago Climate Exchange

The most prominent American carbon market, the Chicago Climate Exchange, began trading in 2003 as a voluntary market for six different greenhouse gases (Clark 2005). CCX sought large businesses and governing entities as consumers and garnered carbon offsets from agricultural producers, mainly the forestry sector (Streck et al 2009). Members could then purchase CCX offsets to comply with the commitments they had made to CCX, described below.

There were two initial phases to the CCX. In phase I, members of the Chicago Climate Exchange made a legally binding commitment to decrease their emissions by 1% every year between 2003 and 2006 (Clark 2005). Each member's baseline emissions were calculated by taking the average of the respective entity's emissions between 1998 and 2001, and the changes in emissions levels were found by comparing current emissions output (minus credits) against the baseline emissions number. Phase II occurred from 2006 through 2010 and required members to achieve emissions levels 6% below their baseline value by 2010. Members had the option of either reducing their own physical emissions (by decreasing production or upgrading to lower carbon technologies) or purchasing carbon offsets through the exchange. Carbon offsets could only be used to fulfill up to 50% of each member's reduction obligation, however. Participation in Phase I was not required to participate in Phase II, although the emissions reductions requirements remained unchanged at 6% below baseline for all Phase II members.

Offsets purchased by members were verified by an approved third-party service to maintain the integrity of the system and give the offsets their value. Objective verification is a necessary component of carbon markets; without it the market would have less price stability and fail to sequester the reported amount of pollutant (Moura Costa et al 1999). To sell offsets on the Chicago Climate Exchange, each offset producer was required to hire their own verification service from a selection of CCX approved firms for an annual verification inspection (De Pinto et al 2010). The offset market was wide in scope. As of 2007, 82 million tons of offsets were generated in just the three years prior from 9,000 farmers on 16 million acres (about the area of South Carolina) of land. Most of these projects were within the United States, but about a quarter were internationally located. To participate in the Chicago Climate Exchange, each offset producer had to prove their method of generating offsets met the requirements for additionality. Their method could not already be required by law and was required to be an “uncommon” practice within their industrial sector. Applications from offset producers were reviewed by an offsets committee within CCX to ensure their project would provide quality emissions offsets, and if approved the measured and verified amount of offsets would be sold on the CCX market.

Companies and municipalities that participated in the CCX did so voluntarily, which is partly what caused the market to eventually fail. While the commitments to reducing emissions were legally binding, supply simply outstripped demand. Up to 50% of CCX offsets could be used to satisfy the emissions reduction targets, but as of 2007 only 15% of reductions achieved under the CCX program came from offsets. Members joined for the opportunity to advertise their “green” stewardship to consumers or out of a sense of social responsibility, but no laws existed requiring heavy polluters to account for their carbon emissions. It appears that when the fiscal crisis of 2008 hit, companies simply lost interest in their own carbon footprint and instead redirected their efforts towards keeping their stock price from plummeting. After Phase II ended in 2010, the Chicago Climate Exchange was no longer trading emissions credits (Spaargaren and Mol 2013) due to lack of demand.

The Kyoto Protocol’s Clean Development Mechanism

Created as a piece of the Kyoto Protocol in 1997, the Clean Development Mechanism (CDM) was a compliance offset tool that was used to meet the carbon emission limits set on each participating country (Barrett 1998). Pioneering the field of carbon offset markets, the CDM faced many challenges over the course of its operation. Its main component involved the funding of emissions reductions projects in lower-income countries by higher-income countries so that the higher income-countries could claim the carbon offsets produced by the project. The market was advertised as a solution to climate change as well as economic stimulus for lower-income countries and thus attracted many supporters (Gillenwater and Seres 2011). A key feature was the flexibility of the mechanism- it allowed countries time to develop and implement low-carbon technologies while funding carbon emissions reductions in lower cost regions of the world (Grubb et al 2010).

Additionality was a major challenge for the Clean Development Mechanism. The scientists behind the CDM worked at creating an extensive set of guidelines and rules to determine if proposed projects would have occurred without the influence of the CDM (Greiner and Michaelowa 2003), and thus they knew that to be effective the mechanism had to be reliable and trustworthy. An Executive Board issued the final decision after discussion about a project, and once approved the offset could be sold in the marketplace. Verification costs also proved to be greater than expected, leading to high transaction costs in the market (Joshi 2012).

The CDM hits its peak in 2008 after being linked with the EU’s Emissions Trading System which created a broader marketplace and encouraged participation (Michaelowa et al 2019). However, this occurred at the same time as the global fiscal crisis, leading to the same outcome as the Chicago Climate Exchange. By linking the CDM and ETS, there was simply an oversupply of credits at a time when demand was dropping. The price of a credit subsequently decreased (Green 2017) to the point where the market was not a worthwhile endeavor for producers. Today, the

CDM still maintains active sequestration projects but does not have anywhere near the level of activity it contained thirteen years ago.

<u>The European Union's Emissions Trading System</u>

In response to new commitments set by the European Union on the amount of carbon dioxide emitted annually, the Emissions Trading System (ETS) was developed as the trading vehicle for the cap and trade system (European Commission 2021). Instead of relying on individuals' voluntary inclinations to purchase carbon offsets like the Chicago Climate Exchange, governments set a cap on the amount of emissions to ensure its targets were met. The cap was to be decreased every year, eventually drawing emissions down to a more sustainable number. This cap and trade method is touted as economically efficient because it will result in the least-costly emissions reductions happening first (Mandell 2008). It also allows for flexibility in the industry for polluters who may not be able to immediately reduce their carbon footprint. If the technology is not readily available but could be developed within a feasible amount of time, firms can choose to buy allowances from the ETS market until they can reduce their own carbon emissions.

Along with the CCX and CDM, the ETS was dramatically affected by the 2008 financial crisis. From 2008-2012, a backlog of credits piled up as extremely limited demand left prices low. However, the European Union commission overseeing the function of the ETS market produced a solution that enabled the system to survive. They introduced a measure that postponed the auctioning off of 900 million carbon credits until 2019 (European Commission 2017). Supply was artificially reduced as a result, which coincided with slowly increasing demand as the world's economies recovered. Prices began to return to pre-recession levels, and the commission was careful to maintain a sustainable balance of credits in the market so as to not force the price to be too high or too low. This solution, called the Market Stability Reserve, serves as an important lesson for carbon markets. The supply of credits in a marketplace can be reduced by temporarily banking credits to ensure prices remain high enough to incentivize production of credits by future projects (Kreibich and Hermwille 2021). Otherwise, trading will come to a halt and the market will have a tough time recovering.

Summary

The three historical carbon markets listed above offer a wealth of information for us to learn from. A multitude of literature has been written discussing aspects of each market, and the modern markets are remarkably similar in some ways. The ETS is notably the only market out of these three that is still trading a high volume of credits today, due to their Market Stability Reserve action. While a similar policy could not be enacted in a voluntary market due to the absence of a single governing body, the individual private marketplaces could adopt policies that restrict the number of new credits if supply within that marketplace gets too high. This would help to ensure that voluntary carbon markets of the present are sustainable in the long term.

Status of Current Programs and Proposals for Carbon Offset Payments to Farmers

Nori

Founded in the fall of 2017, Nori began as a business plan entry in the "ConsenSys Blockchain for Social Impact Hackathon" (Nori 2021). After winning the competition, the business plan was turned into a real company and has been growing quickly. Nori's goal is to enlist agricultural producers to supply carbon offsets through change of practices, then sell those offsets on their own voluntary carbon market (Thompson et al 2021). One crucial aspect of running a successful carbon offset market is having well defined methodology: policies and specific verification methods that are standardized across all suppliers so that each carbon offset credit has equal value. Nori provides this information with their "Croplands Methodology" document, which explains the eligibility of crop types, additionality, length of the project, and the lifecycle of one of their offset credits.

Nori's carbon offsets are called "Nori Removal Tonnes" (NRT) and are equivalent to one metric ton of carbon dioxide removed from the atmosphere. Currently, Nori bases their offsets on the standard of how likely the carbon is to stay in the ground for at least 10 years (Nori 2020). When an NRT is sold, Nori assigns it a score reflecting the likelihood of the carbon meeting this longevity standard. The supplier of the NRT is then paid accordingly. By using a scoring system for longevity, the marketplace innately encourages suppliers to use quality carbon sequestration practices and continue carbon storage into the future.

Similar to the cryptocurrency market, Nori uses blockchain technology to keep track of and verify transactions made in their marketplace (Donnelly 2020). Each NRT produced by one of their suppliers is turned into a token which enables it to be tracked via blockchain (Chen 2018). Consumers of Nori's credits can instantly and securely purchase and receive NRTs, removing costly and time-consuming human-based security actions (Woo et al 2020). Currently each NRT is sold for $15 per metric ton of carbon dioxide plus a 15% transaction fee for Nori's marketplace services, and the supplier of the NRT receives the full $15 purchase price. Once an NRT token is sold, it is immediately retired from the marketplace and cannot be sold further (Nori 2020). These combined practices ensure proper carbon accounting for credits sold by Nori and bar any double counting of offsets.

Indigo Ag

Indigo Ag is a more recent participant in the carbon offsets industry. They began seeking out farmers in early 2021 to provide carbon sequestration credits by practicing regenerative agriculture (Spratt et al 2021). The company's approach is centered around the farmer. Indigo works with farmers to determine the amount of land enrolled in the program, then it is up to the farmer to make changes in the way they farm and send that data to Indigo. The farmer continues to collect and send data to Indigo over the course of the year, and Indigo takes a physical soil sample from selected acres (Indigo 2021). After receiving a farmer's annual data and the results of the soil samples, Indigo calculates the amount of carbon dioxide that has been sequestered and sends the number to Verra, an independent verification firm. They verify the amount of carbon sequestered with their Verified Carbon Standard (VCS) (Verra 2021), and Indigo is then free to market and sell the carbon credits. Once the credits sell, the producer receives payment for their sequestration efforts.

For agricultural producers who register acres with Indigo right now, a potential credit price of $15 per metric ton of carbon dioxide is advertised. Indigo notes that as the market expands, this price is subject to change in response to supply and demand. Several large companies have signed contracts with Indigo already, promising to purchase carbon offsets at a price of $20 per ton (Indigo 2021). The difference between the consumer purchase price and the payment the producer receives goes towards verification of the credits and the upkeep of the marketplace. By aggregating carbon credits to be sold to consumers on the voluntary market, transaction costs between parties are minimized (Wang et al 2021) and theoretically more credits should be exchanged as a result.

The Indigo Carbon market program was created after the company's 2019 Terraton Initiative (Keenor et al 2021), a challenge to sequester one trillion tons of carbon dioxide in the world's soils and improve soil and atmospheric health as a result. Indigo encouraged individuals and teams to innovate and improve on existing technology for sequestration and verification of soil organic carbon, with rewards for the best ideas (UBC 2019). This is just one example of how the need for voluntary carbon markets sparks technological advancement and can result in more carbon dioxide sequestered.

Truterra

A third prominent U.S. voluntary carbon market is Truterra's TruCarbon program. Truterra is farmer-owned and operates Land O'Lakes' sustainability program, currently making TruCarbon the only farmer owned voluntary carbon market available (Boland et al 2020). Its process of generating carbon credits is very similar to those of Nori and Indigo Ag. First, the farmer registers acres with the TruCarbon program and implements one or more change of practices. Throughout the growing and harvesting season, data is collected and sent to Truterra and stratified soil samples are taken and tested after harvest. The stratified soil testing process divides soils into zones that are likely to have similar changes in SOC, and Truterra employs this method to save costs. Using the aggregated data and results from the soil sample tests, Truterra determines additionality and verifies the appropriate amount of carbon sequestered. After verification, the carbon credits go through certification against market standards then can be sold to buyers in the marketplace. Even after the credits are sold, the farmer must continue to provide information on how they are keeping up practices that retain the carbon in the soil (Truterra 2021).

A notable aspect of the TruCarbon program is the willingness to accept carbon sequestration that occurred up to five years ago (Thompson et al 2021). This "look back" policy is different from other modern voluntary carbon markets. Most programs require the registration of acres first, then implementation of the change of practice that satisfies additionality, but Trucarbon is unique in this way. However, as the carbon offset market continues to develop, the focus on higher quality credits that have proven additionality will likely be increased.

As a company that already conducts agricultural business outside of the voluntary carbon markets, Truterra has a valuable resource at its disposal. Data sharing and management are considered to be critical to the success of voluntary carbon markets (Amelung et al 2020). When producers can efficiently organize and send management data to the market aggregator, the quality and therefore marketability of the credits will be higher. Truterra has developed an "insights engine" to streamline the process of reporting additionality and continued stewardship practices. Some commercial bulk purchasers of carbon credits will find value in this additional layer of data when they can market their offsets as being maintained in the soil and have the data to support this claim (Cerri et al 2021).

Challenges Facing Modern Voluntary Carbon Markets

<u>Supply and Demand</u>

One of the main reasons the Chicago Climate Exchange failed is the lack of demand and overabundant supply. The fiscal crisis of 2008 shifted the world's focus from fixing the future to fixing the present, and demand ultimately dried up when companies were forced into survival mode. On the opposite end of the spectrum, between the Clean Development Mechanism, the Emissions Trading System, and the Chicago Climate Exchange there were simply too many sequestration projects verified and producing credits. This led to a large supply of credits with limited buyers (DiPerna 2018).

To maintain a balanced supply of carbon credits that meets demand, firms that are trying to create a carbon market should carefully research the economics of the industry and only register a predetermined number of acres. This will ensure that the price of their carbon offset certificates remains high enough to incentivize the production of more credits and provide producers with fair compensation. Legislation, such as the Growing Climate Solutions Act, focuses on issues surrounding a fair price for farmers to receive for credits and was passed by the Senate but not by the House in June of 2021 (US Senate Committee on Agriculture, Nutrition, and Forestry 2021).

As far as demand goes, much has happened in the eleven years since the end of the CCX. Climate education is now a fundamental part of the scientific curriculum in many school districts around the country (Schreiner et al 2008). Youth movements have begun to affect mainstream politics (O'Brien et al 2018), and the business world is finally seeing the problem for what it is and the opportunities that come with it (Bristow 2021). While still very divided on the issue of climate change politically, the majority of American society is concerned and desires immediate action. The purchase of millions of tons of offsets by Microsoft earlier this year speaks to how desirable the credits are, and other major US companies will soon be looking for similarly large-scale markets to purchase from. Individual consumers who are concerned about climate change will also bolster demand for credits as it has already become somewhat mainstream to offset emissions from flights and other carbon intensive activities.

Verification

Accurate verification of sequestered carbon gives the credits their value and ensures double counting does not occur. Unlike projects like REDD+, which deal with conservation of tropical ecosystems, a majority of carbon sequestration projects in the United States are agriculturally and agroforestry based. Verification standards are necessary to ensure quality offsets (Streck 2020). However, verification processes are time consuming and expensive.

Innovation is lowering the cost of verification through adaptation of technologies like blockchain and will help make verified credits more attainable (Hua et al 2020). Blockchain also improves security in the carbon market as it precisely records every transaction associated with a specific credit, preventing credits being resold and the offset being claimed multiple times. Verification services such as the Greenhouse Gas Protocol and the Verra Verified Climate Standard offer the service to markets resulting from the need for standardized verification (Gifford 2020). To pay for verification, some markets (such as Nori) charge a service fee for every credit purchased. Nori's fee is 15%, and since it is charged on top of the credit price the producer still receives full compensation for any extra costs. This type of policy incentivizes farmers to produce credits for a marketplace that covers verification costs and standardizes the credits sold in the marketplace.

Data Utilization

Each marketplace is different when it comes to data privacy. As there is no tangible physical product being exchanged during carbon sequestration, data sharing is key to creating and verifying the carbon credits (Amelung et al 2020). Market firms need to know how long the carbon will be in the soil, the density of carbon in the soil before and after the change of practice, and current management practices on the acres involved. Markets will have different requirements about data sharing regarding the type, frequency, and availability of the data, so farmers who are considering participating in the market should examine all aspects of the agreement made with the marketplace about data ownership (Brooks 2021).

Longevity of Offsets

To be effective in reducing carbon dioxide levels and preventing the worst effects of climate change, some degree of permanence must be established for the carbon sequestration credits in a marketplace. Agricultural carbon sequestration is unique in that the carbon that has been sequestered can be released again due to improper management. For example, a farmer could change from conventional till to no till and sell carbon credits for his or her land. However, if the land is then sold, or a lease expires, and a new operator manages that ground now they might not continue the same sequestration practices. Re-tilling of the ground would release most of the carbon from the previously sequestered offsets (McLauchlan 2006) and result in invalidation of the credits that had already been sold. For operators of family farms and land that has been held for generations, this will not pose much of an issue but 54% of cropland is rented land in the United States (USDA-ERS and USDA-NASS 2014). If a farmer who rents wants to participate in a carbon market, an agreement will have to be reached with the landlord about the longevity of the offsets. This might entail prevention of certain tillage practices on the land for a specified length of time.

Chapter 2: Science and Effectiveness of Soil Carbon Sequestration

Introduction

A frequently suggested solution to the global problem of climate change is the sequestration of atmospheric carbon dioxide by soils. Because agricultural land is already under management and there are several regenerative agriculture practices available to be implemented, the industry is in a strong position to reduce carbon dioxide levels through farming. Recent studies suggest up to 5 Gt of carbon dioxide per year could be sequestered in soils using these methods (Paustian et al 2019) which would make a significant dent in the problem. The goal of this report is to further investigate these methods for their effectiveness and costs based on reviewing existing scientific literature. Quantitative information about agricultural soil carbon sequestration is valuable to both farmers and the public, so these numbers will be included based on data from a collection of long-term experiments.

Effectiveness of agronomic practices at storing carbon dioxide

Two main agricultural practices have been suggested to sequester carbon in the soil while continuing to grow crops. The first is moving from conventional tillage to no-till, which reduces the amount of exposure to air the soil has and therefore decreases the release of carbon dioxide. The second practice is cover cropping, which puts carbon back into the soil through photosynthesis when a field would otherwise lay fallow. Each of these practices has costs and benefits aside from carbon sequestration, and these will be discussed later. In this section, no-till and cover cropping will be analyzed for their realistic carbon sequestration potential using a collection of scientific studies and other resources.

No-till

In order to understand why switching from conventional till to no-till is effective at sequestering carbon, some background on soil science is needed. When plants perform photosynthesis, their roots carry carbon-containing compounds down the plant and into the soil (Kumar et al 2006). These compounds are released through root respiration and enter the soil as soil organic carbon (SOC). If soil is left undisturbed over time, aggregates (small clumps of soil held together by SOC) form. Aggregation prevents organic matter in the soil from being decomposed by soil microorganisms (NDSU 2021), and since the organic matter is underground, it cannot enter the atmospheric carbon dioxide pool. Additionally, organic litter is left on the surface of the field when the field is not plowed. This further helps to prevent any soil organic matter from decomposing (Ogle et al 2005) although the litter on the surface is still susceptible to decomposition.

When tillage occurs, aggregates are broken up into smaller pieces. At the same time, as the soil is turned and tossed around it is exposed to air. With no aggregation to prevent decomposition plus exposure to sunlight and water, the molecules with carbon begin to break down into gaseous carbon dioxide (Schley et al 2018). Therefore, fields where one crop is grown during the main growing season and lay fallow through the rest of the year have a carbon cycle where more carbon is sequestered as the crop grows and carbon dioxide is released during the remaining 6-8 months (Ogle et al 2012). The opportunity to sequester additional carbon in the soil for a more permanent period comes from the fact that agricultural soils have been depleted of carbon from many years of tillage (Guo and Gifford 2002). One study finds that the decrease is in the range of 30-50% over 50 years of permanent agriculture (Valkama et al 2020). Gradually, the amount of SOC can be built back up using regenerative agriculture methods.

Much scientific analysis has been done on the effectiveness of no-till practices at storing carbon in the soil, and the results vary widely. A 2002 study found that after switching from conventional tillage to no-till, it takes time for soil aggregates to form and meaningful carbon sequestration to begin (West and Post 2002). Their data showed that carbon sequestration rates peak between 5-10 years after the change is made, and the soil reaches the equilibrium point about 15-20 years after no-tillage has been implemented (West and Post 2002). When the equilibrium point is reached, soil sequestration experiences a dramatic decrease. A different scientific study explored the impact of soil aggregates re-forming using a conceptual model representing the multiple stages of macroaggregate formation. The researchers attribute a majority of soil carbon loss to the destruction of macroaggregates during tillage, but not all. Results from the model showed that in fields where no-till was implemented, the number of soil macroaggregates doubled compared to conventionally tilled fields. In addition, the average time for carbon to remain sequestered in the soil also doubled (Six et al 2000). These findings provide support for no-till being an effective carbon sequestration method.

Specific values regarding the efficacy of switching from conventional tillage (moldboard plow) to no-till range from 0.02 to 0.29 metric tons of carbon per acre per year. Valkama et al simulated crop growth over 20 years using no-till methods and data from Kazakhstan, Finland, and Italy. Their simulated measurements reached from 0-30 cm deep into the soil, a standard range for SOC sampling. The results from the simulation showed that sequestration rates of 0.06 to 0.22 metric tons of carbon per acre per year were likely, with the warmer climate areas of study having sequestration rates on the higher end of the spectrum (Valkama et al 2020*). Another study finds comparable results. West and Post 2002 synthesized 67 long-term experiments on changing from conventional till to no-till and worked with SOC data from the 0-30 cm depth. Their findings were that depending on the region and climate, a farmer could expect to sequester between 0.17 and 0.29 metric tons of carbon per acre per year using the no-till method (West and Post 2002*). Finally, two experiments in Ohio study the effect of switching to no-till over multiple decades. One dataset ran for 49 years while the other ran for 47 years, but both returned the same results: average SOC sequestration for the 0-30 cm depth was 0.02 metric tons of carbon per acre per year (Kumar et al 2012*). While this value may seem low, there is a likely explanation. After about 20 years of no-till management, SOC levels tend to plateau. Because the research was over a period of almost 50 years, the annual sequestration is likely lower than it would have been at the 20-year mark.

Not all researchers agree, however. A decade-long experiment indicated that after 10 years there were no significant differences in sequestered SOC between conventional tillage and no-till test plots (Sheehy et al 2015). One proposed explanation for the lack of additional soil carbon in the no-till plot is the no-till plot produced a lower yield than the conventional till plot. With less plant growth comes less soil carbon sequestration, even if the lack of tillage enabled more microaggregates to form. In 2010, researchers compared the results of 69 different studies and determined that switching from conventional till to no-till had “no significant difference” on the amount of carbon sequestered (Luo et al 2010). On average, carbon levels decreased regardless of the tillage method. Luo et al found that carbon levels tended to increase within the first 10 cm of soil but decreased in all levels below 10 cm. However, Luo et al found a different practice to be effective at carbon sequestration. Their results showed greatly increased SOC levels within the first 60 cm of the soil when cropping frequency (the amount of time a field is growing crops) was increased. This result suggests keeping the soil covered with plant growth for as much time as possible is more effective than simply switching to no-till alone and lends support to cover cropping as an efficient method of soil carbon sequestration. Other researchers have also expressed concern about methods used to investigate the carbon sequestering capacity of no-till. Baker et al pointed out how, in many studies that find no-till to positively affect the level of carbon in agricultural soils, the sampling depth of the soils was often 30 cm or less from the surface (Baker et al 2007). As the roots of common U.S. agricultural crops extend far beyond the 30 cm depth (Archontoulis et al 2017), this level of study may not be deep enough to fully understand the effect on SOC throughout the soil horizons.

While still inconclusive about whether switching to no-till agriculture results in carbon sequestration or not, the scientific literature shows us that if sequestration occurs it is not to the level that many carbon offset trading platforms purport it to be. Realistically, a farmer implementing no-till on his or her fields can expect other benefits to the health of the soil but little to no soil carbon sequestration.

<u>Cover cropping</u>

When a farmer grows cover crops in the non-peak growing season, carbon sequestration is happening for many of the same soil chemistry reasons as no-till. The shade produced by cover crop plants reduces the rate of decomposition for any organic matter that might be on the surface of the soil, which helps keep aggregated organic carbon in the soil. But the main reason cover cropping leads to increased SOC is the increase of carbon inputs to the soil (Poeplau and Don

2015). In a time when the soil would otherwise be unproductive, photosynthesis is occurring in the cover crop plants. As photosynthesis occurs, carbon compounds are generated and transported down through the plant's structure. From there, the organic carbon compounds are released into soil in the form of rhizodeposits (Moore et al 2019), increasing the level of soil organic carbon. Additional research using test fields at the University of Minnesota found that SOC levels are inversely related to the amount of time a field is left fallow (Baker and Griffis 2005). In other words, the shorter amount of time a field is left without crops growing in it, the higher its SOC levels, similar to the findings of Luo et al mentioned above. The researchers also found an inverse relationship between soil SOC levels and the frequency and length of fallow periods. These results further support that having plants grow even in off-peak seasons has a positive effect on the amount of carbon stored in the soil.

Analyses on cover cropping studies by Poeplau and Don (2015) found an average positive sequestration rate result. The researchers used data from 139 different plots at 37 sites, and their results showed an average sequestration rate of 0.13 metric tons of carbon per acre per year (Poeplau and Don 2015*). The experiments used in this analysis ranged from 1 to 54 years old and measured carbon dioxide stored in the top 30 cm of the soil (called the plow layer). One interesting estimate from the study was that the soils were expected to reach their level of carbon equilibrium 155 years after the beginning of the practice. Another study measured sequestered SOC from the 0-75 cm depth in Southern Illinois. The experiment ran for 12 years using cover crops with conventional tillage. It was found that on average, cover crop plots sequestered an additional 0.22 metric tons of carbon per acre per year (Olson et al 2014*). Similarly, Ruis and Blanco-Canqui 2017 observed sequestration of 0.2 to 0.42 metric tons of carbon per acre per year due to cover crops (Ruis and Blanco-Canqui 2017*). Another study on the effectiveness of cover crops concluded that it is more common for scientific analyses to find cover cropping increases soil carbon levels than decreases them (Tautges et al 2019). From the results of the experiments and analyses above, a farmer implementing cover crops while still using conventional till could expect to sequester about 0.25 metric tons of soil carbon per acre per year.

As with no-till, there are some scientific articles that report results contrary to those that say cover cropping has a positive effect on the level of SOC. A 2005 study used two fields- one with conventional tillage and only planting in the optimal time of the year, and one using reduced tillage and cover crops- to study the differences cover cropping makes. The researchers reported some SOC increase due to the cover crop, but then a subsequent decrease immediately after the cover crop was killed to prepare for the planting of the main crop in May (Baker and Griffis 2005). After two years, equal carbon levels between the control and test fields led the researchers to conclude that the methods employed in the test field made no difference in the amount of carbon sequestered. However, it can be argued that the timeline of two years is not enough time to conclude that no carbon sequestration was occurring at all. It commonly takes 5 to 10 years for significant changes in soil organic carbon to be noticeable by measuring instruments (Smith 2004), so the study would have benefitted from a longer investigative period.

Another factor influencing the rate of sequestration when a field is under cover crop management is if the cover crop residue is removed or not. This was investigated in 2009, and the researchers found that if organic residue is removed, cover cropping holds “little carbon sequestration potential” (Bavin et al 2009) due to the added exposure to moisture and sunlight. However, this conclusion has been disputed as well. Their findings may be unrepresentative of the soil’s equilibrium condition after the soil microorganisms have had time to adjust and reproduce to the new environment of additional organic carbon. Bavin et al, the authors of the article, even suggest their findings are more representative of what happens when a farmer begins to use cover crops and no-till. As stated above, it usually takes years of adjustment for the soil to begin meaningful sequestration (Smith 2004).

Combined practices

From the literature I reviewed, no-till and cover crops are more effective at carbon sequestration when used in conjunction with each other. Luo et al concluded that when cover cropping was combined with no-till agriculture, significant increases in soil carbon levels were the result (Luo et al 2010). “Significant” was defined as observing a greater than 11% increase in carbon over a 5-year timeline and considering most agricultural soils are carbon depleted 30-50% from their natural states (Valkama et al 2020) this appears to be a good definition. A different analysis of no-till and cover cropping being used together found an annual net carbon sequestration value of 0.36 metric tons of carbon per acre (Hollinger et al 2005*). Corn and soybeans were studied in this experiment because they are two of the most widely grown crops in the United States, confirming that carbon sequestration is possible for these crops.

Other experiments find similarly positive results. An experiment by Ruis and Blanco-Canqui 2017 observed increases of 0.15 to 0.29 metric tons of carbon per acre per year using test plots with no-till and cover crops (Ruis and Blanco-Canqui 2017*). Valkama et al 2020 found comparable results of 0.25 to 0.26 metric tons of carbon per acre per year from a simulation of 20 years of growing cycles (Valkama et al 2020*). The parameters of the simulation included measuring 0-30 cm in soil depth, rotation of crops each growing season, and leaving organic residues on the field. Another study measured to a greater depth, 75 cm into the ground. The study lasted for 12 years in Southern Illinois, and the results were positive: 0.49 metric tons of carbon per acre per year (Olson et al 2014*).

Depending on the depth of the soil sample, a farmer using both no-till and cover crops could realistically expect to sequester from 0.25 to 0.45 metric tons of soil carbon per acre per year.

<u>Other practices</u>

In addition to permanent operational changes made to a field, one-time actions can also result in sequestered carbon. These include spreading manure or biochar on a field, which are usually used to add nutrients back into the soil but can have the added benefit of carbon sequestration. Manure and biochar decompose much more slowly than newly dead biomass, helping to both retain carbon longer when mixed in with the soil (Paustian et al 2016) and provide cover from the sun as light increases the rate of decomposition. The specific rate of carbon sequestration from spreading manure was studied in a 2019 scientific article. Using test crop plots at the University of California, researchers found that 0.55 metric tons of carbon per acre were sequestered annually by the manure-fertilized plots compared to the conventionally managed plots (Tautges et al 2019*). However, the transfer of carbon here is not from the atmospheric carbon pool into the soil through photosynthesis but rather is a transfer of organic matter from one location to a larger carbon sink.

Biochar is a newer method of adding carbon back to a field. It is produced using pyrolysis, a method of heating organic matter to an elevated temperature with low concentrations of oxygen present (Wang et al 2015). Application of biochar to fields is considered a “frontier technology” as more research needs to be done to explore how it can be implemented in a cost-effective way on a wide scale as well as fully understand its long-term effects. Biochar is much more resistant to decay by soil microbes due to the chemical reactions it undergoes during pyrolysis, and therefore is estimated to remain in its solid form for over one hundred years (Wang et al 2015). It also can cause plants to be more productive, accelerating the growth of roots into the soil and the rate of photosynthesis (Paustian et al 2019). However, spreading manure or biochar are single actions. Unlike no-till or cover cropping, which are management practices used for the whole season, these actions are usually taken as needed to provide plants with additional nutrients. Therefore, they do not seem to be eligible to generate carbon credits because there is no permanent change of practice.

Logistics of carbon sequestration with each practice

Longevity of sequestered carbon

When considering the value of carbon offsets produced, permanence (how long the sequestered carbon is expected to stay in the soil) is a major factor. The lower the amount of time expected (or less confidence in the value) the lower the value of the generated offset will be. Permanence values of 100 years are common for afforestation carbon sequestration projects, but it is very difficult, if not impossible, for farmers to commit to land management practices that will exceed their lifetime (Von Unger and Emmer 2018). Some carbon markets require permanence times of 25 years, but even this can be a stretch for a farmer to commit to. The concern regarding permanence is that without the requirement that the change in practice be maintained for a set amount of time, even one year of not doing the practice could erase any gains in SOC. Multiple studies confirm this. A 2018 report by the World Resources Institute found that when farmers return to conventional tillage after practicing no-till, much of the sequestered soil organic carbon is lost to the atmosphere (Mulligan et al 2018). No-till encourages the production of soil aggregates over several growing seasons, but tilling a field immediately breaks down those aggregates and they are susceptible to decomposition. Another article confirms this. The 2005 study on the human impacts on soil carbon concluded that once an additionality practice is no longer used, the sequestered carbon will rapidly return to the atmosphere (Smith 2005).

There is evidence to support combining regenerative agricultural practices to attempt to extend the permanence value of sequestered carbon. In a research effort to determine effective ways to enhance soil carbon stocks in soils, researchers found that when no-till and a variety of rotational crops are used in conjunction, sequestered carbon stays in the ground for a greater period than either no-till with monoculture or conventional till with rotational crops (Marland et al 2004). Similar to the findings of Luo et al 2010, these results encourage the use of multiple carbon sequestration farming methods to sequester more carbon.

Regional variation due to soil types and climate

Agriculture around the world is affected by numerous regional factors, including climate and soil type. As one might imagine, these factors influence the rate of possible agricultural carbon sequestration as well. Because precipitation is needed for crop production, agricultural activity is limited at high latitude areas such as Northern Canada (<15 inches of precipitation per year) and Siberia (6-20 inches of precipitation per year). For comparison, Nebraska ranges from 14-32 inches of precipitation per year. Therefore, SOC sequestration is not effective in these higher latitude areas (Smith 2012).

One in-depth analysis published in 2012 is particularly helpful. Ogle et al created a model that used data from 74 studies on the effect of no-till on carbon sequestration rates to find which regions of the U.S. have the greatest sequestration potential. The analysis covered both corn and wheat as these are some of the most widely grown crops. Their results for corn were that as you move farther North in the United States, agricultural soils have greater carbon sequestration potential when using no-till agriculture (Figure 1, Ogle et al 2012). Accompanying this result, there is also greater predicted longevity of sequestered carbon farther North. The difference in potential occurs because areas that are cooler and dryer have lower rates of decay than hot and wet coastal areas. The model returned mixed results when using the data on winter wheat. Under no-till management, SOC levels are expected to decrease in the Mid-Atlantic and corn belt regions but increase in the Northern Great Plains and the South (Figure 2, Ogle et al 2012). While this data should not solely be used to make a decision about farm management practices, it is important to keep in mind when considering the benefits of switching from conventional tillage to no-till.

Figure 1: The top half of figure 1 shows the average change in carbon soil inputs from corn residues. The lower half of figure 1 shows the steady-state of soil organic carbon levels after the change from conventional tillage to no-till in corn growing fields (Ogle et al 2012).

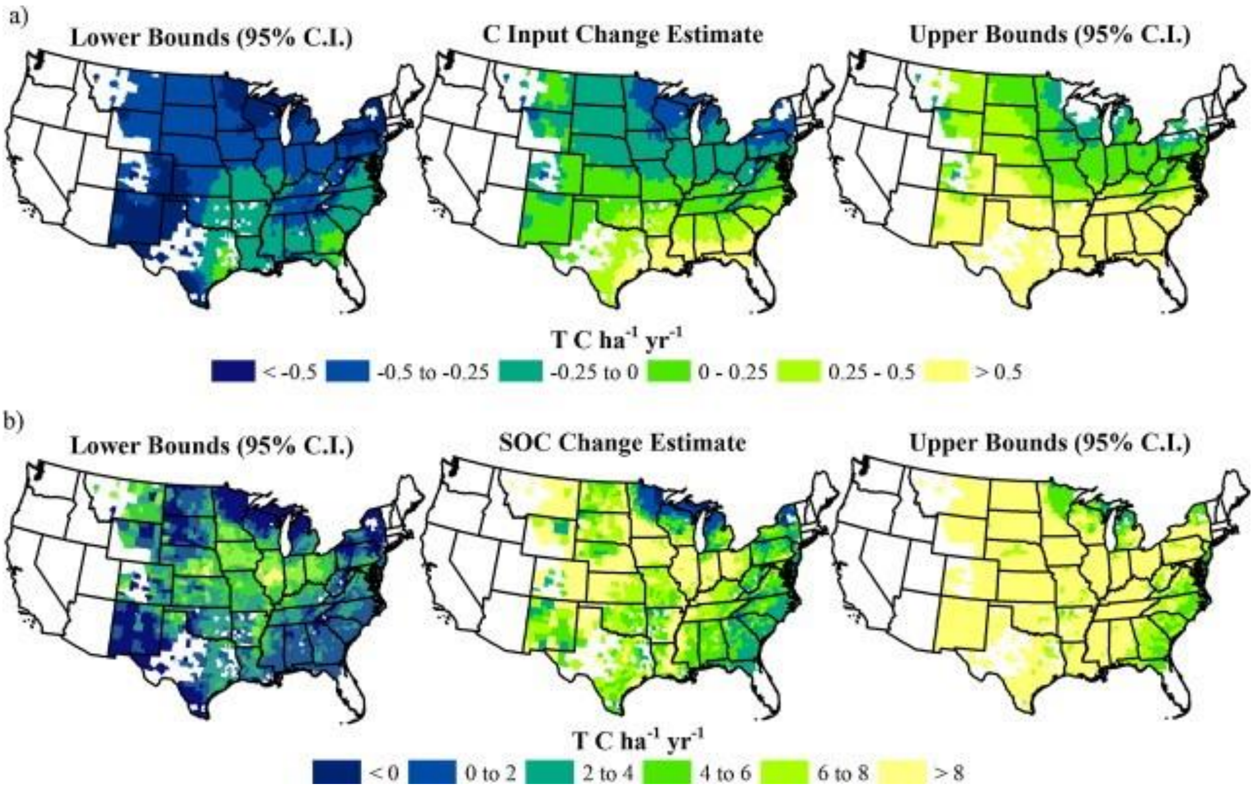
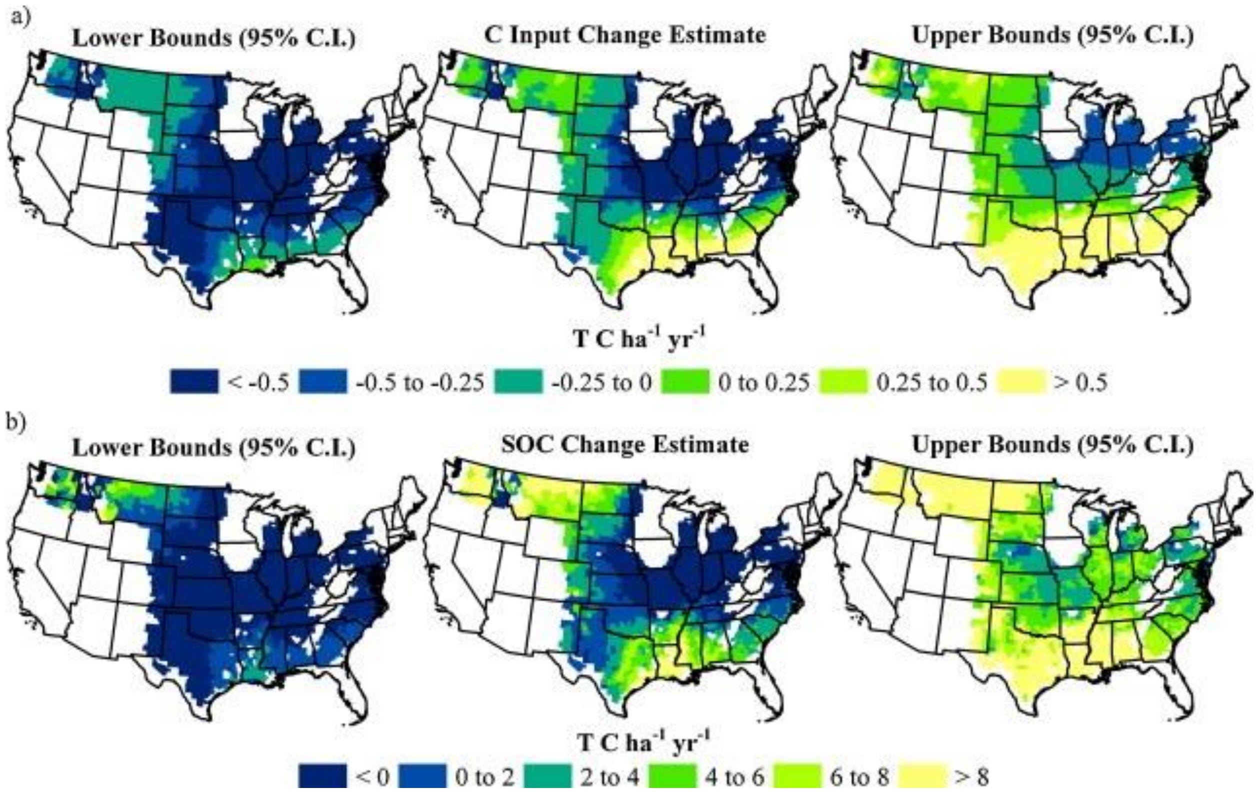


Figure 2: The top half of figure 2 shows the average change in carbon soil inputs from winter wheat residues. The lower half of figure 2 shows the steady-state of soil organic carbon levels after the change from conventional tillage to no-till in winter wheat growing fields (Ogle et al 2012).



<u>Maximum levels of stored SOC</u>

Even though there is a deficit in the amount of carbon in agricultural soils compared to non-agricultural soils, the amount of carbon soils can hold is limited. Soil ecosystems maintain a balance of carbon and other nutrients, and the amount of carbon that can be stored in soil is called attainable organic carbon. Net primary productivity (NPP) can be used to measure the rate of biomass accumulation in plants and determines how much carbon moves through the roots of a plant to be stored underground. Therefore, if NPP can be increased, the attainable level of SOC can also be increased (Ingram and Fernandes 2001). Saturation of carbon in the soil occurs when natural soil chemical balances prevent additional carbon inputs from sequestering SOC (West and Six 2006). When the change of management practice is first implemented, carbon inputs are greater than outputs. SOC level reaches a steady state when carbon inputs are equal to outputs, and saturation is reached. At this point, carbon is still lost from the soil but is replaced by newly sequestered carbon equal to the value lost. This means that the soil is still actively sequestering carbon, just at a lower rate than when the soil was not yet carbon saturated. Additionally, the effects of climate on decomposition rates can be lessened by vegetation such as cover crops (Ingram and Fernandes 2001).

Additional costs and benefits of each agronomic practice

As with any management practice, there are costs to implement no-till and cover cropping. However, there are also some additional soil health and environmental benefits. Because the soil is not being turned over every year in no-till, yields might decrease (Lerohl and Van Kooten 1995). The economic impact of possible decreases in yield was studied in 2005. Researchers found that on average, farmers using no-till earned an average of $11.33 less per acre than farmers who used conventional tillage methods (Manley et al 2005*). The lowest difference in net revenue was in the Southern U.S. where no-till producers only lost a dollar per acre on average; the highest was in the corn belt where producers lost about $20 per acre on average. The cost of cover crops has been studied in a similar way. Using a cost assessment model, researchers were able to determine that implementing cover crops costs a farmer an average of $11.74 per acre per year with current USDA programs (Roley et al 2016*). Additional planting time, fuel, seeds, and fertilizer all contribute to these added costs.

With the added costs come numerous environmental benefits that arise from switching to no-till or cover crops. Soil erosion is a major problem in much of the central United States, and both no-till and cover crops can decrease the rate at which soils are lost (Hobbs et al 2008). Water is also conserved using conservation agriculture (Li et al 2011), and fertilizer runoff is decreased greatly.

Nitrous oxide is a potent greenhouse gas and can enter the atmosphere through nutrient runoff and overapplication of Nitrogen fertilizer. Cover crops decrease runoff and take up excess soil nitrogen, so nitrous oxide emissions might be reduced as a benefit of cover crops (Mulligan et al 2018). There are other direct benefits of increasing SOC levels, some of which are increased cycling of nutrients, enhanced filtration of water, and minimized soil compaction (Reicosky 2003). Reducing the amount of fertilizer and/or water needed for a crop can decrease management costs, so it is possible these benefits could help farmers decide on operational practices going forward.

The effect on crop yield of switching from conventional tillage to no-till depends on the type of crop being grown. Toliver et al (2012) report that on average, sorghum and wheat experienced increased yields under no-till management while corn yields were lower than their conventional tillage counterparts. The possible difference in yield will be either an added cost or added revenue based on the crop grown and is an additional factor to consider.

Current levels of adoption

Data taken from the USDA-NASS's 2017 census of agriculture shows that farmers are increasingly moving to no-till and away from conventional tillage. The census of agriculture is taken once every 5 years, so the 2017 version is the most up to date. It shows that since the previous census in 2012, the number of agricultural acres under no-till has increased by 8% (USDA-NASS 2017). Midwestern states lead with the highest number of no-till acres in production with Kansas, Nebraska, and Iowa at the top of the list. The data show that cover crop adoption is growing at an even faster rate. Between the 2012 census and the 2017 census, the number of acres under cover crop management increased by 50% (USDA-NASS 2017) with Midwestern states again leading the shift. Under most voluntary carbon credit schemes, these acreages for which practices have already changed would not be eligible for carbon credits because of the additionality requirement, which requires that payments be made only for sequestration that occurs in addition to that being achieved without the carbon credit

Summary

One purpose of this report was to investigate the prospects for voluntary carbon offset markets for agricultural practices that potentially sequester carbon while still allowing the crop to be grown. Other practices, such as the conversion of cropland to native grasslands or the planting of trees have been shown to result in higher SOC values over time (Niu and Duiker 2006) but do not allow the land to continue to grow crops. One important aspect of this investigation was to examine existing agronomic literature that could help to identify the soil carbon sequestration potential of various practices. While scientific research has found that using cover crops or cover crops in conjunction with no-till on-average leads to positive soil carbon sequestration, the values are not as high as some values that have been reported in the media. There exists potential for meaningful SOC sequestration in productive agricultural lands, but whether it will be profitable for farmers to implement the changes in practice will depend on the price they receive for any offset credits generated.

Chapter 3: Economic Analysis of WTP and WTA for Carbon Credits

The economic concepts of willingness to accept (WTA) and willingness to pay (WTP) allow economists to estimate supply and demand curves for a good or service. In this case, the goal is to measure the price farmers would accept for a carbon credit depending on the change in practice used to sequester the carbon. Once these prices are known, they can be compared to the prices consumers are willing to pay for the good or service. If the price consumers are willing to pay is above the price producers are willing to accept, the transaction will occur. A series of WTA values can be used to approximate a supply curve. The supply curve would start at the lowest price producers are willing to accept and run parallel to the x-axis for the quantity of products producers are willing to supply for that price. Then, the supply curve would make a discrete movement upward to the next lowest price and again continue parallel to the x-axis for the amount producers are willing to supply. Until the data is exhausted, this process can be repeated to produce a stair-stepped supply curve that approximates the actual supply curve for the voluntary agricultural carbon credit market. Figure 3 shows the theoretical supply curve along with the WTP price produced from this report.

Willingness to Accept

The WTA prices for the practices of no-till, cover crops, and the combination of both no-till and cover crops was produced using previously researched data on average costs to implement each practice. Traditional microeconomic thinking is employed here: producers are willing to accept at minimum the amount it costs them to produce a product. While the costs used to generate WTA prices are an average of what has been found in existing literature, they are not necessarily accurate of every farmer's situation. Costs of switching from conventional tillage to no-till vary based on existing equipment the farmer might have access to as no-till agriculture requires a special type of planter that injects seed directly into the soil. It also depends on the type of crop being grown as the yields of some crops may be affected by the change to no-till. Additional data on implementation costs of no-till and cover crops would make Figure 3 more representative of current market conditions. However, due to time constraints, this was not possible. Figure 3 is intended to be a theoretical framework for how a supply curve could be constructed to approximate the supply of agriculturally produced carbon credits and uses a limited data set as an example. An expansion of this data set would better approximate real-world prices.

Willingness to Pay

Willingness to pay values for carbon credits are more easily found. Voluntary marketplaces have historically sold credits in large quantities as contracts with companies and organizations that desire to offset their carbon emissions, but recently some markets have begun to sell individual credits directly to consumers. Nori, a private firm based in Seattle, Washington currently sells one Nori Removal Token (NRT) for $15 plus a 15% charge for a total of $17.25. Nori's website explains that $15 goes directly to the farmer who produced the offset and the 15% fee goes to Nori to "help keep the marketplace running" (Nori 2021). One NRT is equivalent to one metric ton of carbon dioxide removed from the atmosphere. This is a standard measurement for carbon offsets and is also used in the Oil Price Information Service's (OPIS) carbon offset reports. The OPIS carbon report from February 2nd, 2022 shows prices around $16 per metric ton of sequestered carbon dioxide. As the OPIS report is an aggregation of prices in multiple voluntary markets and firms, $16 per metric ton of carbon dioxide was used as the WTP value for this analysis.

However, there is a difference between sequestered carbon and sequestered carbon dioxide. The molecular weight of one carbon atom is 12.01 grams per mol, while the molecular weight of carbon dioxide, which is made up of one carbon atom and two oxygen atoms, is 44.01 grams per mol.

When 44.01 is divided by 12.01, the result is 3.664. This value can be used to convert between the price for one ton of sequestered carbon dioxide and the price for one ton of sequestered carbon. Multiplying $16 per ton of sequestered carbon dioxide by 3.664 indicates the value of one ton of sequestered carbon is $58.63. Therefore, $58.63 is used as a comparison to the cost of sequestering one ton of soil carbon. The WTP curve is represented as a horizontal line at the price of $58.63 in Figure 3.

Economic Implications

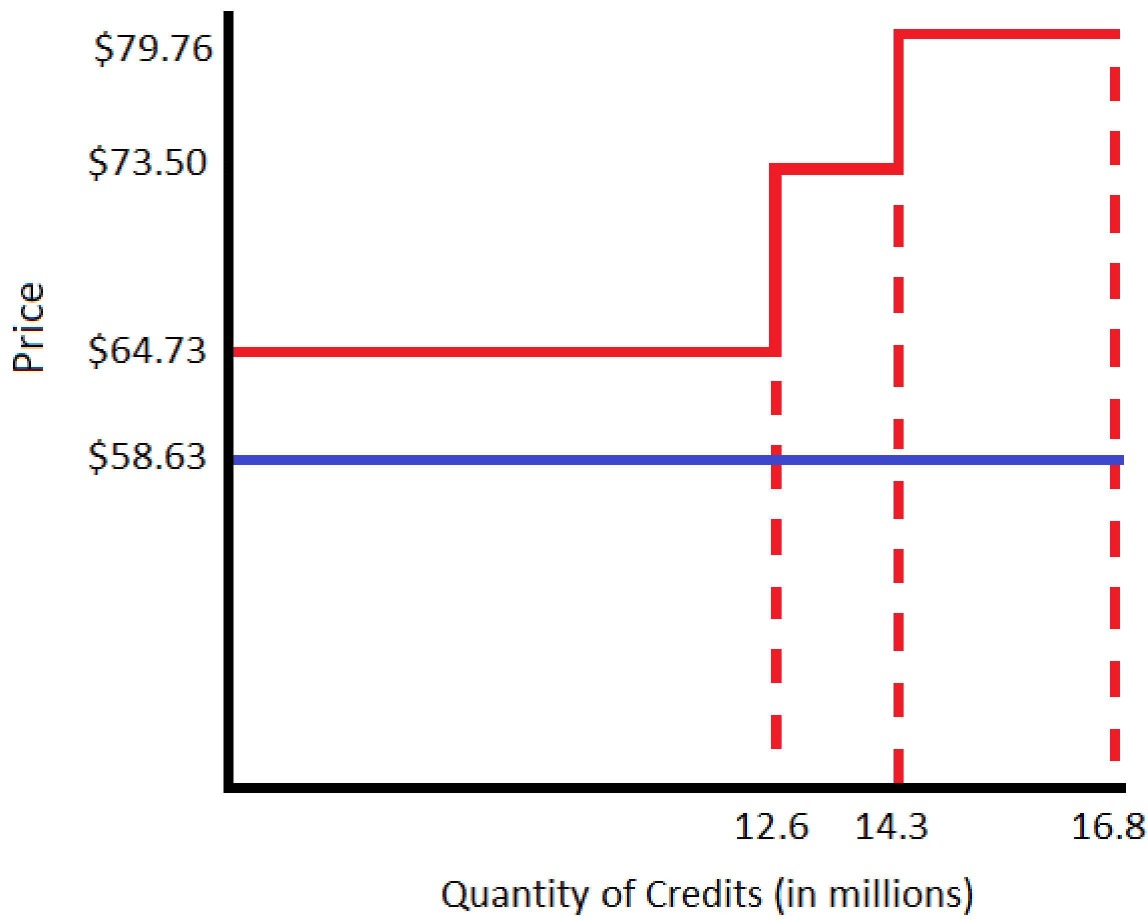
Noticeably, the WTP price is lower than any of the WTA prices in Figure 3. As stated above, transactions occur when WTP prices are higher than WTA prices and both producers and consumers gain utility from the transaction. According to Figure 3, no agricultural carbon credits would be purchased or sold in this marketplace. The graph still provides us with valuable information though. If consumers were willing to pay between $64.73 and $73.50, 12.6 million credits would be sold. Because no-till is the lowest cost method of sequestering atmospheric carbon in agricultural soil, these credits would all be produced by farmers switching from conventional till to no-till. The next least cost practice is cover crops. Figure 3 shows that an additional 1.7 million credits would be traded if consumers were willing to pay between $73.50 and $79.76 per metric ton of sequestered carbon. Implementing both additionality practices at once on the same acre of land costs the most and therefore produces the highest cost credits. If consumers were willing to pay greater than $79.76 an additional 2.5 million credits would be sold for a total of 16.8 million credits traded in the marketplace. As it is though, consumers are generally not willing to pay these higher prices for carbon credits.

However, these transactions are occurring in the real-world marketplace even though Figure 3 suggests they should not be. There are several possible reasons for the discrepancy. First, due to the limited amount of data used to create the supply curve, Figure 3 might be unrepresentative of true market conditions. Three sequestration values found through scientific literature were used to get the average sequestration for no-till and cover crops, and four values were used for the average sequestration when both practices are used. A greater number of data points would improve the accuracy of the estimated sequestration per acre of each practice. There is also a wide range of values in the literature about the cost per acre of implementing no-till or cover crops due to regional variations and climate factors. If Figure 3 was created using data from a single region with homogenous agricultural characteristics, it would better represent the local costs to implement changes. Subsequently, the prices producers are willing to accept would be more accurate as well.

Another possible explanation as to why carbon credit transactions are occurring at a price of $58.63 is that farmers might not be receiving fair compensation. If the data used to create Figure 3 are representative of the true costs of the changes in practice, then farmers are not being paid an amount equivalent to their expenses to do the change in practice. However, there are other benefits to both no-till and cover crops besides monetizable soil carbon sequestration. Improved soil health, water management, and reduced soil erosion are all effects of using regenerative agricultural practices as well. If a monetary value can be placed on these benefits, the cost of making the change in practice might make financial sense for the farmer. Future research on this topic would be useful.

While Figure 3 differs from what is happening in the voluntary carbon credit market right now, it is still useful as a model for how to estimate the supply curve of agriculturally produced credits. More data would improve its accuracy, or it could be used in a more localized way that measures the cost of producing credits in a specific region. Either way, the framework used to build the supply curve and WTP line in Figure 3 could be replicated in other studies.

Figure 3: WTA and WTP for carbon credits produced by agricultural soil sequestration of carbon. The red stair-stepped line represents a supply curve based on the costs of soil carbon sequestration for different practices. The blue line represents a WTP price based on current market data.



Conclusion

Voluntary carbon markets and soil carbon sequestration are two of many important tools we have available to help reverse the consequences of the climate crisis. It is encouraging to see a resurgence of interest in the industry, although both consumers and producers require more information than is available to fully understand the benefits and potential drawbacks. Education can come from a variety of sources: popular articles, scientific literature, university extension services, etc. Every method of carbon sequestration and emissions reduction has pros and cons, and it is important to remember that these solutions can be used in concert with one another to meet emissions reductions goals. Regional differences, political atmospheres, and market systems will contribute to which methods are suitable for a specific area. But the baseline is this: consumers desire carbon sequestration credits, and agricultural producers have a way to potentially monetize their effort into producing the credits. The two groups just need to be connected.

References

Amelung, W., Bossio, D., de Vries, W., Kögel-Knabner, I., Lehmann, J., Amundson, R., Bol, R., Collins, C., Lal, R., Leifeld, J., Minasny, B., Pan, G., Paustian, K., Rumpel, C., Sanderman, J., van Groenigen, J. W., Mooney, S., van Wesemael, B., Wander, M., & Chabbi, A. (2020). Towards a global-scale soil climate mitigation strategy. Nature Communications, 11(1). https://doi.org/10.1038/s41467-020-18887-7

Andrade de Sá, S., & Daubanes, J. (2016). Limit pricing and the (in)effectiveness of the carbon tax. Journal of Public Economics, 139, 28–39. https://doi.org/10.1016/j.jpubeco.2016.04.006

Archontoulis, S., & Licht, M. (2017, June 14). How fast and deep do corn roots grow in Iowa? How Fast and Deep do Corn Roots Grow in Iowa? | Integrated Crop Management. Retrieved January 4, 2022, from https://crops.extension.iastate.edu/cropnews/2017/06/how-fast-and-deep-do-corn-roots-grow-iowa

Baker, J. M., & Griffis, T. J. (2005). Examining strategies to improve the carbon balance of corn/soybean agriculture using eddy covariance and mass balance techniques. Agricultural and Forest Meteorology, 128(3-4), 163–177. https://doi.org/10.1016/j.agrformet.2004.11.005

Baker, J. M., Ochsner, T. E., Venterea, R. T., & Griffis, T. J. (2007). Tillage and soil carbon sequestration—what do we really know? Agriculture, Ecosystems & Environment, 118(1-4), 1–5. https://doi.org/10.1016/j.agee.2006.05.014

Barrett, S. (1998). Political economy of the Kyoto Protocol. Oxford Review of Economic Policy, 14(4), 20–39. https://doi.org/10.1093/oxrep/14.4.20

Bavin, T. K., Griffis, T. J., Baker, J. M., & Venterea, R. T. (2009). Impact of reduced tillage and cover cropping on the greenhouse gas budget of a maize/soybean rotation ecosystem. Agriculture, Ecosystems & Environment, 134(3-4), 234–242. https://doi.org/10.1016/j.agee.2009.07.005

Bessy, C., & Chauvin, P.M. (2013). The power of Market Intermediaries: From information to Valuation Processes. Valuation Studies, 1(1), 83–117. https://doi.org/10.3384/vs.2001-5992.131183

Boland, M. A., Briggeman, B. C., Jacobs, K., Kenkel, P., McKee, G., & Park, J. L. (2020). Research priorities for agricultural cooperatives and their farmer-members. Applied Economic Perspectives and Policy, 43(2), 573–585. https://doi.org/10.1002/aepp.13068

Boulatoff, C., Boyer, C., & Ciccone, S. J. (2013). Voluntary environmental regulation and firm performance: The Chicago climate exchange. The Journal of Alternative Investments, 15(3), 114–122. https://doi.org/10.3905/jai.2012.15.3.114

Boyce, J. K. (2018). Carbon pricing: Effectiveness and equity. Ecological Economics, 150, 52–61. https://doi.org/10.1016/j.ecolecon.2018.03.030

Bristow, S. (2021). Business and climate Change: Rising public Awareness creates significant opportunity. United Nations. https://www.un.org/en/chronicle/article/business-and-climate-change-rising-public-awareness-creates-significant-opportunity

Brooks, R. (2021, February 26). New carbon Market Initiative announced BY Corteva | AgWeb. AgWeb. https://www.agweb.com/news/business/conservation/new-carbon-market-initiative-announced-corteva.

Burtraw, D. (2000). Innovation Under the Tradable Sulfur Dioxide Emission Permits Program in the U.S. Electricity Sector. https://ageconsearch.umn.edu/record/10599/.

Calel, R., & Dechezleprêtre, A. (2016). Environmental policy and Directed Technological Change: Evidence from the European carbon market. Review of Economics and Statistics, 98(1), 173–191. https://doi.org/10.1162/rest_a_00470

CCX. (2010). Program-Wide Baseline and Compliance Reports. Chicago Climate Exchange. https://web.archive.org/web/20100424202311/http://www.chicagoclimatex.com/content.jsf?id=250.

Center for Climate and Energy Solutions. (2021). Comments of the Center for Climate and Energy Solutions. Retrieved June 15, 2021, from https://www.c2es.org/wp-content/uploads/2021/04/c2es-comments-USDA-climate-smart-agriculture-forestry-strategy.pdf.

Cerri, C. E., Rezende de Vita, C. L., Zylbersztajn, D., Karantininis, K., Fujihara, M. A., & Giordano, S. R. (2021). Overview of Policies and Institutional Frameworks on GHG Emissions in EU, China, Africa, with Special Reference to the Role of Agriculture. Cadernos Da

Universidade Do Café, 11. https://www.researchgate.net/profile/Samuel-Giordano-2/publication/351334483_C_A_D_E_R_N_OS_DA_U_N_I_V_E_R_S_I_DA_D_E_D_O_C_A_F_E_Vol_11/links/6091abfba6fdccaebd091f7f/C-A-D-E-R-N-OS-DA-U-N-I-V-E-R-S-I-DA-D-E-D-O-C-A-F-E-Vol-11.pdf#page=99.

Chen, D. (2018). Utility of the blockchain for climate mitigation. The Journal of the British Blockchain Association, 1(1), 1–9. https://doi.org/10.31585/jbba-1-1-(6)2018

Chen, Y.-hua, Wang, C., Nie, P.-yan, & Chen, Z.-rui. (2020). A clean innovation comparison between carbon tax and cap-and-trade system. Energy Strategy Reviews, 29, 100483. https://doi.org/10.1016/j.esr.2020.100483

Clark, N. (2005, December). Chicago Climate Exchange Inc. https://unfccc.int/files/meetings/cop_11/climate_talk_series/application/pdf/cop11_kiosk_clark.pdf.

Climate Justice Alliance. (2017). Carbon Pricing: A Critical Perspective for Community Resistance, 1. http://www.ienearth.org/wp-content/uploads/2017/11/Carbon-Pricing-A-Critical-Perspective-for-Community-Resistance-Online-Version.pdf.

Corbera, E., Estrada, M., & Brown, K. (2009). How do regulated and voluntary carbon-offset schemes compare? Journal of Integrative Environmental Sciences, 6(1), 25–50. https://doi.org/10.1080/15693430802703958

Curtis, E. M. (2014). Who loses under power plant cap-and-trade programs? National Bureau of Economic Research. https://doi.org/10.3386/w20808

De Pinto, A., Magalhaes, M., & Ringler, C. (2010). The potential of carbon markets for small farmers: A literature review. https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.455.234&rep=rep1&type=pdf.

DiPerna, P. (2018). Pricing carbon: Integrating promise, practice and lessons learned from the Chicago climate exchange. Designing a Sustainable Financial System, 115–148. https://doi.org/10.1007/978-3-319-66387-6_5

Donnelly. (2020, September 11). Enhancing investment in soil health and carbon storage: Frontiers for linking finance and carbon accounting. https://www.slideshare.net/cgiarclimate/enhancing-investment-in-soil-health-and-carbon-storage-frontiers-for-linking-finance-and-carbon-accounting.

European Commission. (2017, February 16). Market stability Reserve. Climate Action - European Commission. https://ec.europa.eu/clima/policies/ets/reform_en.

Fang, X., Du, Y., & Qiu, Y. (2017). Reducing carbon emissions in a Closed-loop production routing problem with simultaneous pickups and deliveries Under carbon Cap-and-Trade. Sustainability, 9(12), 2198. https://doi.org/10.3390/su9122198

Fankhauser, S., & Hepburn, C. (2010). Designing carbon markets, part ii: Carbon markets in space. Energy Policy, 38(8), 4381–4387. https://doi.org/10.1016/j.enpol.2010.03.066

Farleigh, A. (2003). The Chicago Climate Exchange: Can Greenhouse Gases be Reduced Absent Government Mandates? Sustainable Development Law & Policy, 3(1). https://digitalcommons.wcl.american.edu/cgi/viewcontent.cgi?referer=https://scholar.google.com/&httpsredir=1&article=1396&context=sdlp.

Gale, D. (1955). The Law of Supply and Demand. Mathematica Scandinavica, 3(1), 155–169. https://login.libproxy.unl.edu/login?qurl=https://www.jstor.org/stable/24490348.

Gans, W., & Hintermann, B. (2013). Market effects of voluntary Climate action BY Firms: Evidence from the Chicago Climate exchange. Environmental and Resource Economics, 55(2), 291–308. https://doi.org/10.1007/s10640-012-9626-7

Gevrek, Z. E., & Uyduranoglu, A. (2015). Public preferences for carbon tax attributes. Ecological Economics, 118, 186–197. https://doi.org/10.1016/j.ecolecon.2015.07.020

Ghil, M. (2002). Natural Climate Variability. Encyclopedia of Global Environmental Change, 1, 544–549. https://www.academia.edu/download/31093484/MGEGEC.pdf

Gifford, L. (2020). "You can't value what you can't measure": A critical look at forest carbon accounting. Climatic Change, 161(2), 291–306. https://doi.org/10.1007/s10584-020-02653-1

Gilbertson, T. (2017). Carbon Pricing: A critical perspective for community resistance. CJA and EIN, 1. Retrieved June 17, 2021, from http://www.ienearth.org/wp-content/uploads/2017/11/Carbon-Pricing-A-Critical-Perspective-for-Community-Resistance-Online-Version.pdf.

Gillenwater, M., & Seres, S. (2011). The Clean Development Mechanism: A Review of the First International Offset Program. Center for Climate and Energy Solutions. https://www.c2es.org/document/the-clean-development-mechanism-a-review-of-the-first-international-offset-program/.

Giller, K. E., Hijbeek, R., Andersson, J. A., & Sumberg, J. (2021). Regenerative agriculture: An agronomic perspective. Outlook on Agriculture, 50(1), 13–25. https://doi.org/10.1177/0030727021998063

Green, J. F. (2017). Don't link carbon markets. Nature, 543(7646), 484–486. https://doi.org/10.1038/543484a

Greiner, S., & Michaelowa, A. (2003). Defining investment additionality for CDM projects—practical approaches. Energy Policy, 31(10), 1007–1015. https://doi.org/10.1016/s0301-4215(02)00142-8

Grubb, M., Laing, T., Counsell, T., & Willan, C. (2010). Global carbon mechanisms: Lessons and implications. Climatic Change, 104(3-4), 539–573. https://doi.org/10.1007/s10584-009-9791-z

Guigon, P. (2010). Voluntary Carbon Markets : How Can They Serve Climate Change Policies. OECD Environmental Working Paper No. 19, 2010, OECD publishing, © OECD. doi: 10.1787/5km975th0z6h-en

Guo, L. B., & Gifford, R. M. (2002). Soil Carbon Stocks and land use change: A meta analysis. Global Change Biology, 8(4), 345–360. https://doi.org/10.1046/j.1354-1013.2002.00486.x

Hausman, J. A. (1981). Exact Consumer's Surplus and Deadweight Loss. The American Economic Review, 71(4), 662–676. https://www.jstor.org/stable/1806188?casa_token=FGtLAyWHcD4AAAAA%3AmNbmPF4VLr1sDddF3bXqQRdsmNyXgM7ExPiBV4wV6CKlroeQ6vU3F3ej1biAKhqjOCrgYB2dETYeEo0jDBG0WpOvCHnbcITc6cxd87bS-N9e8kVDpG4&seq=1#metadata_info_tab_contents.

Haya, B., Cullenward, D., Strong, A. L., Grubert, E., Heilmayr, R., Sivas, D. A., & Wara, M. (2020). Managing uncertainty in carbon offsets: Insights from California's standardized approach. Climate Policy, 20(9), 1112–1126. https://doi.org/10.1080/14693062.2020.1781035

Hobbs, P. R., Sayre, K., & Gupta, R. (2008). The role of conservation agriculture in sustainable agriculture. Philosophical Transactions of the Royal Society B, 363(1491). https://doi.org/https://doi.org/10.1098/rstb.2007.2169

Hollinger, S. E., Bernacchi, C. J., & Meyers, T. P. (2005). Carbon budget of mature no-till ecosystem in North Central Region of the United States. Agricultural and Forest Meteorology, 130(1-2), 59–69. https://doi.org/10.1016/j.agrformet.2005.01.005

Hua, W., Jiang, J., Sun, H., & Wu, J. (2020). A blockchain based peer-to-peer trading framework integrating energy and carbon markets. Applied Energy, 279, 115539. https://doi.org/10.1016/j.apenergy.2020.115539

Indigo. (2021). Enrich Your Soil, Improve Your Profit Potential with Carbon by Indigo. https://www.indigoag.com/carbon/for-farmers.

Indigo. (2021). First Companies Commit to Purchasing Verified Agricultural Carbon Credits through Indigo Carbon, a Critical Step in the Transition to Beneficial Agriculture. https://www.indigoag.com/pages/news/first-companies-commit-to-purchasing-verified-agricultural-carbon-credits.

Ingram, J. S. I., & Fernandes, E. C. M. (2001). Managing carbon sequestration in soils: Concepts and terminology. Agriculture, Ecosystems & Environment, 87(1), 111–117. https://doi.org/10.1016/s0167-8809(01)00145-1

Jarke-Neuert, J., & Perino, G. (2020). Energy efficiency promotion backfires under cap-and-trade. Resource and Energy Economics, 62, 101189. https://doi.org/10.1016/j.reseneeco.2020.101189

Joshi, G. R. (2012). Clean Development Mechanism in the Context of Climate Change Mitigation. In Climate change and UNFCCC Negotiation Process (pp. 51–60). essay.

Kaufman, N. (2016). Carbon Tax vs. Cap-and-Trade: What's a Better Policy to Cut Emissions? World Resources Institute. https://www.wri.org/insights/carbon-tax-vs-cap-and-trade-whats-better-policy-cut-emissions.

Keenor, S. G., Rodrigues, A. F., Mao, L., Latawiec, A. E., Harwood, A. R., & Reid, B. J. (2021). Capturing a soil carbon economy. Royal Society Open Society, 8(4). https://royalsocietypublishing.org/doi/full/10.1098/rsos.202305.

Kitchens, C. (2020). Carbon Markets in Agriculture: A Market-Based Conservation Solution. R Street Shorts, 96. https://www.rstreet.org/wp-content/uploads/2020/10/Final-No-96-Carbon-Markets.pdf.

Kollmuss, A., Zink, H., & Polycarp, C. (2008). Making Sense of the Voluntary Carbon Market A Comparison of Carbon Offset Standards. WWF. https://www.globalcarbonproject.org/global/pdf/WWF_2008_A%20comparison%20of%20C%20offset%20Standards.pdf.

Kreibich, N., & Hermwille, L. (2021). Caught in Between: Credibility and feasibility of the voluntary carbon market post-2020. Climate Policy, 21(7), 939–957. https://doi.org/10.1080/14693062.2021.1948384

Kuhns, R. J., & Shaw, G. H. (2018). The carbon dioxide problem and solution. Navigating the Energy Maze, 99–115. https://doi.org/10.1007/978-3-319-22783-2_12

Kumar, R., Pandey, S., & Pandey, A. (2006). Plant roots and carbon sequestration. Current Science, 91(7), 885–890. Retrieved from https://www.jstor.org/stable/24094284.

Kumar, S., Kadono, A., Lal, R., & Dick, W. (2012). Long-term no-till impacts on organic carbon and properties of two contrasting soils and corn yields in Ohio. Soil Science Society of America Journal, 76(5), 1798–1809. https://doi.org/10.2136/sssaj2012.0055

Lal, R. (2004). Soil carbon sequestration to mitigate climate change. Geoderma, 123(1-2), 1–22. https://doi.org/10.1016/j.geoderma.2004.01.032

Lal, R. (2018). Digging deeper: A holistic perspective of factors affecting soil organic carbon sequestration in agroecosystems. Global Change Biology, 24(8), 3285–3301. https://doi.org/10.1111/gcb.14054

Lanzi, E., Chateau, J., & Dellink, R. (2012). Alternative approaches for levelling carbon prices in a world with fragmented carbon markets. Energy Economics, 34(2), S240–S250. https://www.sciencedirect.com/science/article/pii/S0140988312001867.

Le Quere, C., Andrew, R. M., Friedlingstein, P., Sitch, S., Pongratz, J., et al. (2018). Global Carbon Budget 2017. Earth Systyem Science Data, 10(1), 405–448. https://essd.copernicus.org/articles/10/405/2018/.

Lerohl, M. L. (1995). Is soil erosion a problem on the Canadian Prairies? Prairie Forum, 20(1). Retrieved from https://www.researchgate.net/publication/40206101_Is_soil_erosion_a_problem_on_the_Canadian_Prairies.

Li, L., Huang, G.-bao, Zhang, R., Bill, B., Guangdi, L., & Kwong, Y. C. (2011). Benefits of conservation agriculture on soil and water conservation and its progress in China. Agricultural Sciences in China, 10(6), 850–859. https://doi.org/10.1016/s1671-2927(11)60071-0

Li, W., Yang, G., & Li, X. (2019). Modeling the evolutionary nexus between carbon dioxide emissions and economic growth. Journal of Cleaner Production, 215, 1191–1202. https://doi.org/10.1016/j.jclepro.2019.01.100

Lin, B., & Li, X. (n.d.). The effect of carbon tax on per capita CO2 emissions. Energy Policy, 39(9), 5137–5146. https://www.sciencedirect.com/science/article/pii/S0301421511004502.

Lin, Boqiang, and Zhijie Jia. "The Energy, Environmental and Economic Impacts of Carbon Tax Rate and Taxation Industry: A CGE Based Study in China." Energy 159 (September 15, 2018): 558–68. https://doi.org/10.1016/j.energy.2018.06.167.

Liu, L., Chen, R., & He, F. (2015). How to promote purchase of carbon offset products: Labeling vs. calculation? Journal of Business Research, 68(5), 942–948. https://doi.org/10.1016/j.jbusres.2014.09.021

Lovell, H., & Liverman, D. (2010). Understanding carbon offset technologies. New Political Economy, 15(2), 255–273. https://doi.org/10.1080/13563460903548699

Luo, Z., Wang, E., & Sun, O. J. (2010). Can no-tillage stimulate carbon sequestration in agricultural soils? A meta-analysis of paired experiments. Agriculture, Ecosystems & Environment, 139(1-2), 224–231. https://doi.org/10.1016/j.agee.2010.08.006

Mandell, S. (2008). Optimal mix of emissions taxes and cap-and-trade. Journal of Environmental Economics and Management, 56(2), 131–140. https://doi.org/10.1016/j.jeem.2007.12.004

Manley, J., van Kooten, G. C., Moeltner, K., & Johnson, D. W. (2005). Creating carbon offsets in agriculture through no-till cultivation: A meta-analysis of costs and carbon benefits. Climatic Change, 68(1-2), 41–65. https://doi.org/10.1007/s10584-005-6010-4

Marland, G., Garten, C. T., Post, W. M., & West, T. O. (2004). Studies on enhancing carbon sequestration in soils. Energy, 29(9-10), 1643–1650. https://doi.org/10.1016/j.energy.2004.03.066

McLauchlan, K. (2006). The nature and longevity of agricultural impacts on soil carbon and nutrients: A review. Ecosystems, 9(8), 1364–1382. https://doi.org/10.1007/s10021-005-0135-1

Metcalf, G. E. (2019). On the Economics of a Carbon Tax for the United States. Brookings Papers on Economic Activity, 405–484. https://muse.jhu.edu/article/740191/summary?casa_token=EkoRw25wZpYAAAAA:_Fm574ZElGpPQd7WO9AzMnkEdntO7RTl2tTdqu3A-hJWsGg8bfyghSD6Cwa9DhCuC2cQPmwNjA.

Michaelowa, A. (2011). Failures of global carbon markets and cdm? Climate Policy, 11(1), 839–841. https://doi.org/10.3763/cpol.2010.0688

Michaelowa, A., Shishlov, I., & Brescia, D. (2019). Evolution of international carbon markets: Lessons for the Paris Agreement. Wiley Interdisciplinary Reviews: Climate Change, 10(6). https://doi.org/10.1002/wcc.613

Mizrach, B. (2012). Integration of the global carbon markets. Energy Economics, 34(1), 335–349. https://doi.org/10.1016/j.eneco.2011.10.011

Moore, J. A., Sulman, B. N., Mayes, M. A., Patterson, C. M., & Classen, A. T. (2019). Plant roots stimulate the decomposition of complex, but not simple, Soil Carbon. Functional Ecology, 34(4), 899–910. https://doi.org/10.1111/1365-2435.13510

Moura Costa, P., Salmi, J., Simula, M., & Wilson, C. (1999). Financial Mechanisms for Sustainable Forestry. UNDP Programme on Forests. https://core.ac.uk/download/pdf/48031381.pdf.

Mulligan, J., Ellison, G., Gasper, R., & Rudee, A. (2018). Carbon removal in forests and farms in the United States. World Resources Institute: Working Papers. Retrieved from https://wriorg.s3.amazonaws.com/s3fs-public/carbon-removal-forests-farms-united-states_0.pdf.

NDSU. (2021). Aggregation. NDSU Soil Health. Retrieved January 2, 2022, from https://www.ndsu.edu/soilhealth/soil-health/soil-property-1/aggregation/

Niu, X., & Duiker, S. W. (2006). Carbon sequestration potential by afforestation of marginal agricultural land in the Midwestern U.S. Forest Ecology and Management, 223(1-3), 415–427. https://doi.org/10.1016/j.foreco.2005.12.044

Nori. (2020, November 2). Croplands Methodology. https://storage.googleapis.com/nori-prod-cms-uploads/croplands_methodology_fd89c6144d/croplands_methodology_fd89c6144d.pdf.

Nori. (2021). How the Nori Marketplace Works: Generating NRTs. https://nori.com/generate-nrts.

Nori. (2021). Nori is Reversing Climate Change. https://nori.com/about.

O'Brien, K., Selboe, E., & Hayward, B. M. (2018). Exploring youth activism on climate change: Dutiful, disruptive, and dangerous dissent. Ecology and Society, 23(3). https://doi.org/10.5751/es-10287-230342

Ogle, S. M., Breidt, F. J., & Paustian, K. (2005). Agricultural management impacts on soil organic carbon storage under moist and dry climatic conditions of temperate and tropical regions. Biogeochemistry, 72(1), 87–121. https://doi.org/10.1007/s10533-004-0360-2

Ogle, S. M., Breidt, J., Easter, M., Williams, S., Killian, K., & Paustian, K. (2010). Scale and uncertainty in modeled soil organic carbon stock changes for US croplands using a process-based model. Global Change Biology, 16(2), 810–822. https://onlinelibrary.wiley.com/doi/full/10.1111/j.1365-

2486.2009.01951.x?casa_token=h31uybowRh0AAAAA%3Art2cmmGp6-gLz1MMiPjo7ngXgqd8B_MSvKriuMxnDgsnDrBhIJVm-Dgtx-XOI0xl8rZqIbpovWMuQg.

Ogle, S. M., Swan, A., & Paustian, K. (2012). No-till management impacts on crop productivity, carbon input and soil carbon sequestration. Agriculture, Ecosystems & Environment, 149, 37–49. https://doi.org/10.1016/j.agee.2011.12.010

Olson, K., Ebelhar, S. A., & Lang, J. M. (2014). Long-term effects of cover crops on crop yields, soil organic carbon stocks and sequestration. Open Journal of Soil Science, 04(08), 284–292. https://doi.org/10.4236/ojss.2014.48030

OPIS. (2022). OPIS Global Carbon Offsets Report. Retrieved from https://www.opisnet.com/product/pricing/spot/carbon-market-report/.

Osborne, T. (2015). Tradeoffs in carbon commodification: A political ecology of common property forest governance. Geoforum, 67, 64–77. https://doi.org/10.1016/j.geoforum.2015.10.007

Paustian, K., Larson, E., Kent, J., Marx, E., & Swan, A. (2019). Soil C sequestration as a biological negative emission strategy. Frontiers in Climate, 1. https://doi.org/10.3389/fclim.2019.00008

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G. P., & Smith, P. (2016). Climate-smart soils. Nature, 532, 49–57. https://doi.org/10.1038/nature17174

Poeplau, C., & Don, A. (2015). Carbon sequestration in agricultural soils via cultivation of cover crops – a meta-analysis. Agriculture, Ecosystems & Environment, 200, 33–41. https://doi.org/10.1016/j.agee.2014.10.024

Post, W. M., Peng, T.-H., Emanuel, W. R., King, A. W., Dale, V. H., & DeAngelis, D. L. (1990). The Global Carbon Cycle. American Scientist, 78. http://www.as.wvu.edu/biology/bio463/globalcarbon.pdf.

Reicosky, D. C. (2003). Conservation Agriculture: Global Environmental Benefits of soil carbon management. Conservation Agriculture, 3–12. https://doi.org/10.1007/978-94-017-1143-2_1

Ribaudo, M., Greene, C., Hansen, L. R., & Hellerstein, D. (2010). Ecosystem services from agriculture: Steps for expanding markets. Ecological Economics, 69(11), 2085–2092. https://doi.org/10.1016/j.ecolecon.2010.02.004

Roley, S. S., Tank, J. L., Tyndall, J. C., & Witter, J. D. (2016). How cost-effective are cover crops, wetlands, and two-stage ditches for nitrogen removal in the Mississippi River Basin? Water Resources and Economics, 15, 43–56. https://doi.org/10.1016/j.wre.2016.06.003

Rubin, J. D. (1996). A model of intertemporal emission trading, banking, and borrowing. Journal of Environmental Economics and Management, 31(3), 269–286. https://doi.org/10.1006/jeem.1996.0044

Ruis, S. J., & Blanco-Canqui, H. (2017). Cover crops could offset crop residue removal effects on soil carbon and other properties: A Review. Agronomy Journal, 109(5), 1785–1805. https://doi.org/10.2134/agronj2016.12.0735

Rushforth, J., Berman, J., & VanLaningham, P. (2021, June 16). Voluntary carbon credits: What they are, why they matter. Voluntary Carbon Credits: what they are, why they matter | S&P Global Platts. https://www.spglobal.com/platts/en/market-insights/podcasts/platts-future-energy/061621-voluntary-carbon-credits-co2-offset-energy-transition-emissions.

Sabbaghi, O., & Sabbaghi, N. (2016). The Chicago Climate exchange and Market Efficiency: An empirical analysis. Environmental Economics and Policy Studies, 19(4), 711–734. https://doi.org/10.1007/s10018-016-0171-4

Schattenberg, P. (2021, May 27). Is carbon farming the 'crop' of the future? AgriLife Today. https://agrilifetoday.tamu.edu/2021/05/27/is-carbon-the-crop-of-the-future/.

Schillie, T. (n.d.). Carbon Markets. Valuing Ecosystem Services. https://www.fs.fed.us/sustainableoperations/documents/susops-summit07-carbon_markets_treyschillie.pdf.

Schley, I., Ruis, S., Blanco, H., & Jasa, P. (2018, February 13). Long-term tillage and soil CO2 fluxes. CropWatch. Retrieved January 4, 2022, from https://cropwatch.unl.edu/2018/long-term-tillage-and-soil-co2-fluxes

Schreiner, C., Henriksen, E. K., & Kirkeby Hansen, P. J. (2008, March 28). Climate education: Empowering today's youth to meet tomorrow's challenges. Studies in Science Education, 41(1), 3–49. https://doi.org/10.1080/03057260508560213

Selvaraju, R. (2012). Climate risk assessment and management in agriculture. In Building resilience for adaptation to climate change in the fisheries and aquaculture sector (pp. 71–89). essay, OECD. Retrieved June 5, 2021, from https://www.researchgate.net/profile/Dw_Brown/publication/281616682_Building_resilience_for_adaptation_to_climate_change_in_the_fisheries_and_aquaculture_sector/links/55eff9cc08ae199d47c03946/Building-resilience-for-adaptation-to-climate-change-in-the-fisheries-and-aquaculture-sector.pdf#page=78.

Sheehy, J., Regina, K., Alakukku, L., & Six, J. (2015). Impact of no-till and reduced tillage on aggregation and aggregate-associated carbon in Northern European agroecosystems. Soil and Tillage Research, 150, 107–113. https://doi.org/10.1016/j.still.2015.01.015

Six, J., Elliott, E. T., & Paustian, K. (2000). Soil macroaggregate turnover and Microaggregate Formation: A mechanism for C sequestration under no-tillage agriculture. Soil Biology and Biochemistry, 32(14), 2099–2103. https://doi.org/10.1016/s0038-0717(00)00179-6

Smith, P. (2004). How long before a change in soil organic carbon can be detected? Global Change Biology, 10(11), 1878–1883. https://doi.org/10.1111/j.1365-2486.2004.00854.x

Smith, P. (2005). An overview of the permanence of Soil Organic Carbon Stocks: Influence of direct human-induced, indirect and natural effects. European Journal of Soil Science, 56(5), 673–680. https://doi.org/10.1111/j.1365-2389.2005.00708.x

Smith, P. (2012). Soils and climate change. Current Opinion in Environmental Sustainability, 4(5), 539–544. https://doi.org/https://doi.org/10.1016/j.cosust.2012.06.005

Sokol, N. W., Kuebbing, S. E., Karlsen-Ayala, E., & Bradford, M. A. (2018). Evidence for the primacy of living root inputs, not root or shoot litter, in forming soil organic carbon. New Phytologist, 221(1), 233–246. https://doi.org/10.1111/nph.15361

Spaargaren, G., & Mol, A. P. J. (2013). Carbon flows, carbon markets, and low-carbon lifestyles: reflecting on the role of markets in climate governance. Environmental Politics, 22(1), 174–193. https://doi.org/10.1080/09644016.2013.755840

Spratt, E., Jordan, J., Winsten, J., Huff, P., van Schaik, C., Jewett, J. G., Filbert, M., Luhman, J., Meier, E., & Paine, L. (2021). Accelerating regenerative grazing to tackle farm, environmental, and societal challenges in the upper Midwest. Journal of Soil and Water Conservation, 76(1). https://doi.org/10.2489/jswc.2021.1209a

Stavins, R. N. (2008). Addressing climate change with a Comprehensive US cap-and-trade system. The Economics and Politics of Climate Change, 24(2), 298–321. https://doi.org/10.1093/acprof:osobl/9780199573288.003.0010

Stavins, R. N. (2008). Cap-and-Trade or a Carbon Tax? The Environmental. https://oconnell.fas.harvard.edu/files/stavins/files/column_22.pdf.

Stevens, A., Udelhoven, T., Denis, A., Tychon, B., Lioy, R., Hoffmann, L., & van Wesemael, B. (2010). Measuring soil organic carbon in croplands at regional scale using airborne imaging spectroscopy. Geoderma, 158(1-2), 32–45. https://doi.org/10.1016/j.geoderma.2009.11.032

Stockmann, U., Adams, M. A., Crawford, J. W., Field, D. J., & Henakaarchchi, N. (2013). The knowns, known unknowns and unknowns of sequestration of soil organic carbon. Agriculture, Ecosystems & Environment, 164, 80–99. https://www.sciencedirect.com/science/article/pii/S0167880912003635.

Streck, C. (2020). Who owns Redd+? Carbon markets, carbon rights and entitlements to Redd+ finance. Forests, 11(9), 959. https://doi.org/10.20944/preprints202007.0288.v1

Streck, C., Tuerk, A., & Schlamadinger, B. (2009). Foresty offsets in emissions trading systems: A link between systems? Mitigation and Adaptation Strategies for Global Change, 14(5), 455–463. https://doi.org/10.1007/s11027-009-9175-8

Subbarao, S., & Lloyd, B. (2011). Can the Clean Development Mechanism (CDM) deliver? Energy Policy, 39(3), 1600–1611. https://doi.org/10.1016/j.enpol.2010.12.036

Tautges, N. E., Chiartas, J. L., Gaudin, A. C., O'Geen, A. T., Herrera, I., & Scow, K. M. (2019). Deep soil inventories reveal that impacts of cover crops and compost on soil carbon sequestration differ in surface and subsurface soils. Global Change Biology, 25(11), 3753–3766. https://doi.org/10.1111/gcb.14762

Thompson, N. M., Hughes, M. N., Nuworsu, E. K. M., Reeling, C. J., Armstrong, S. D., Mintert, J. R., Langemeier, M. R., Delay, N. D., & Foster, K. A. (2021, June). Opportunities and challenges associated with "carbon farming" for U.S. row-crop producers. https://ag.purdue.edu/commercialag/home/resource/2021/06/opportunities-and-challenges-associated-with-carbon-farming-for-u-s-row-crop-producers/.

Tol, R. S. J. (2009). The Economic Effects of Climate Change. Journal of Economic Perspectives, 23(2), 29–51. https://www.aeaweb.org/articles?id=10.1257/jep.23.2.29.

Toliver, D. K., Larson, J. A., Roberts, R. K., English, B. C., De La Torre Ugarte, D. G., & West, T. O. (2012). Effects of no-till on yields as influenced by crop and environmental factors. Agronomy Journal, 104(2), 530–541. https://doi.org/10.2134/agronj2011.0291

Truterra. (2021). The Process of Transforming On-Farm Stewardship into Farm-Generated Carbon Credits. https://www.truterraag.com/getmedia/2f784735-b827-4a65-8e41-8bfdbd5c3924/Truterra-carbon-credit-v1.pdf.

Turvey, R. (2000). Goods and Bads. World Economics. https://ideas.repec.org/a/wej/wldecn/34.html.

UBC. (2019). The Terraton Challenge by Indigo Ag. http://ires.ubc.ca/the-terraton-challenge-by-indigo-ag/.

US Senate Committee on Agriculture, Nutrition, and Forestry. (2021, June 24). Growing climate solutions act Passes U.S. senate: The United States Senate Committee on Agriculture, nutrition & Forestry. Majority News | Newsroom | The United States Senate Committee On Agriculture, Nutrition & Forestry. https://www.agriculture.senate.gov/newsroom/dem/press/release/growing-climate-solutions-act-passes-us-senate.

USDA-ERS and USDA-NASS. (2014). Farmland ownership and tenure. USDA ERS - Farmland Ownership and Tenure. https://www.ers.usda.gov/topics/farm-economy/land-use-land-value-tenure/farmland-ownership-and-tenure/.

USDA-NASS. (2017). Census land use practices - USDA. Retrieved January 4, 2022, from https://www.nass.usda.gov/Publications/Highlights/2020/census-land-use-practices.pdf

USDA-NASS. (2017). United States Summary and State Data. Geographic Area Series, 1(51). https://www.nass.usda.gov/Publications/AgCensus/2017/Full_Report/Volume_1,_Chapter_1_US/usv1.pdf.

USDA-NASS. (2019, April). Farm Producers. https://www.nass.usda.gov/Publications/Highlights/2019/2017Census_Farm_Producers.pdf.

USDA-NASS. (2020). Farms and Land in Farms 2019 Summary. Census of Agriculture. https://www.nass.usda.gov/Publications/Todays_Reports/reports/fnlo0220.pdf.

USGCRP. (2017). Fourth National Climate Assessment: Summary Findings. In Climate science special report: Fourth National Climate Assessment. essay, U.S. Global Change Research Program. Retrieved June 21, 2021.

Valkama, E., Kunypiyaeva, G., Zhapayev, R., Karabayev, M., Zhusupbekov, E., Perego, A., Schillaci, C., Sacco, D., Moretti, B., Grignani, C., & Acutis, M. (2020). Can conservation agriculture increase soil carbon sequestration? A modelling approach. Geoderma, 369. https://doi.org/10.1016/j.geoderma.2020.114298

Van Der Ploeg, F., & Withagen, C. (2014). Growth, renewables, and the Optimal carbon tax. International Economic Review, 55(1), 283–311. https://doi.org/10.1111/iere.12049

VandenBygaart, A. J., Yang, X. M., Kay, B. D., & Aspinall, J. D. (2002). Variability in carbon sequestration potential in no-till soil landscapes of Southern Ontario. Soil and Tillage Research, 65(2), 231–241. https://doi.org/10.1016/s0167-1987(02)00003-x

Varadarajan, R. (2020). Market exchanges, negative externalities and sustainability. Journal of Macromarketing, 40(3), 309–318. https://doi.org/10.1177/0276146720926525

Verra. (2021). About Verra. https://verra.org/about-verra/who-we-are/.

Von Unger, M., & Emmer, I. (2018). Carbon Market Incentives to Conserve, Restore and Enhance Soil Carbon. The Nature Conservancy. Retrieved from https://biblioteca.semarnat.gob.mx/janium/Documentos/Ciga/libros2018/CD004004.pdf.

Wang, J., Xiong, Z., & Kuzyakov, Y. (2015). Biochar stability in Soil: Meta-analysis of decomposition and priming effects. GCB Bioenergy, 8(3), 512–523. https://doi.org/10.1111/gcbb.12266

Wang, M., McCarl, B., Wei, H., & Shiva, L. (2021). Unintended consequences of agricultural participation in voluntary carbon markets: Their nature and avoidance. Complexity, 2021, 1–17. https://doi.org/10.1155/2021/9518135

Watson, F. (2021, January 29). Microsoft buys 1.3 million carbon offsets in 2021 portfolio. S&P Global Platts. https://www.spglobal.com/platts/en/market-insights/latest-news/coal/012921-microsoft-buys-13-million-carbon-offsets-in-2021-portfolio.

West, T. O., & Post, W. M. (2002). Soil organic carbon sequestration rates by tillage and crop rotation. Soil Science Society of America Journal, 66(6), 1930–1946. https://doi.org/10.2136/sssaj2002.1930

West, T. O., & Six, J. (2006). Considering the influence of sequestration duration and carbon saturation on estimates of Soil Carbon Capacity. Climatic Change, 80(1-2), 25–41. https://doi.org/10.1007/s10584-006-9173-8

White, C. (2020). Why regenerative agriculture? American Journal of Economics and Sociology, 79(3), 799–812. https://doi.org/10.1111/ajes.12334

Williams III, R. C., Gordon, H. G., Burtraw, D., Carbone, J. C., & Morgenstern, R. D. (2015). The initial incidence of a carbon tax across income groups. SSRN Electronic Journal, 68(1), 195–214. https://doi.org/10.2139/ssrn.2537839

Woo, J., Asutosh, A. T., Li, J., Ryor, W. D., Kibert, C. J., & Shojaei, A. (2020). Blockchain: A theoretical framework for better application of carbon credit acquisition to the building sector. Construction Research Congress 2020. https://doi.org/10.1061/9780784482858.095

Wood, J. (2018). The Pros and Cons of Carbon Taxes and Cap-and-Trade Systems. The School of Public Policy Publications, 11(30). https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3289810.

Yan, X., Cai, Z., Wang, S., & Smith, P. (2011). Direct measurement of soil organic carbon content change in the croplands of China. Global Change Biology, 17(3), 1487–1496. https://doi.org/10.1111/j.1365-2486.2010.02286.x

Yang, G., Sun, T., Wang, J., & Li, X. (2019). Modeling the nexus between carbon dioxide emissions and economic growth. Journal of Cleaner Production, 215, 1191–1202. https://doi.org/10.1016/j.enpol.2015.06.031

Yang, T. (2006). The Problem of Maintaining Emission "Caps" in Carbon Trading Programs Without Federal Government Involvement: A Brief Examination of the Chicago Climate Exchange and the Northeast Regional Greenhouse Gas Initiative. Fordham Environmental Law Review, 17(2), 271–286. https://www.jstor.org/stable/44174885?seq=1#metadata_info_tab_contents.

Yin, Y., & Lawphongpanich, S. (2006). Internalizing emission externality on road networks. Transportation Research Part D: Transport and Environment, 11(4), 292–301. https://doi.org/10.1016/j.trd.2006.05.003