US Agriculture as a Carbon Sink: From International Agreements to Farm Incentives

Oranuch Wongpiyabovorn, Alejandro Plastina, John Crespi

Working Paper 21-WP 627
November 2021

Center for Agricultural and Rural Development
Iowa State University
Ames, Iowa 50011-1070
www.card.iastate.edu

Oranuch Wongpiyabovorn is PhD Student, Department of Economics, Iowa State University. E-mail: oranuchw@iastate.edu.

Alejandro Plastina is Associate Professor, Department of Economics, Iowa State University. E-mail: plastina@iastate.edu.

John Crespi is Professor, Department of Economics, Iowa State University. E-mail: jcrespi@iastate.edu.

For questions or comments about the contents of this paper, please contact Alejandro Plastina, plastina@iastate.edu.

U.S. Agriculture as a Carbon Sink: From International Agreements to Farm Incentives

Oranuch Wongpiyabovorn, Alejandro Plastina, and John Crespi[1]

Abstract.

This article examines voluntary agricultural carbon programs in the United States, the policy of international agreements to prevent further global warming, and reviews literature related to that policy and its impact on U.S. carbon programs. We discuss international, national, and regional carbon pricing mechanisms that provide the market signals to consumers and suppliers of carbon credits in detail in order to compare and contrast different programs that impact agricultural carbon markets. Economic descriptions of the programs are derived. This article is useful for those who wish to know how U.S. policy currently influences agricultural carbon markets as well as how proposals may need to be structured in order to avoid potential market obstacles.

Key words. agriculture, carbon credits, carbon sequestration, CO2, global warming, greenhouse gasses, monitoring, policy, verification

The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (IPCC 2021) asserts the average global surface temperature reached 1.09°C (1.9°F) above pre-industrial levels in 2011-2020, with larger increases over land (1.59°C) than over oceans (0.88°C). The warming temperatures affect ecosystems, wildlife, and human health. Burke et al. (2015) estimate that if no further action on global warming is adopted, global income will decline 23% by 2100 compared to the case of no climate change. In addition, the economic impact is projected to be stronger in warmer countries, which are more likely to be poorer countries. For instance, a combination of meltwater from glaciers and thermal expansion of seawater would raise sea levels, destroying coastal habitats, causing wetland flooding, and contaminating agricultural soils with salt.

---

[1] Wongpiyabovorn is a doctoral student, Plastina is an associate professor and Crespi is a professor in the Department of Economics, Iowa State University. Plastina is also a faculty affiliate of the Center for Agricultural and Rural Development (CARD), Crespi is CARD Director. The contribution of each author to this article is Wongpiyabovorn 60%; Plastina 35%; and Crespi 5%.

According to the United Nations Framework Convention on Climate Change (UNFCCC) (2011), climate change is the result of human-induced greenhouse gas (GHG) emissions that increase atmospheric GHG concentration and change global weather patterns. In the United States, the Environmental Protection Agency (EPA) (2021a) estimates that 80% of GHG emissions in 2019 were from carbon dioxide (CO2), primarily from fossil fuel use. Other major GHGs include methane (CH4), nitrous oxide (N2O), and fluorinated gases. Generally, other GHG emissions are measured in terms of CO2 equivalent (CO2e) for comparison on the basis of their global warming potential (i.e., how much energy the emissions of 1 metric ton (Mt) of a gas will absorb over a given period of time, relative to the emissions of 1 MtCO2). The EPA assigns global warming potentials of 28-36, 265-298, and in the thousands or tens of thousands, respectively, to CH4, N2O, and fluorinated gases over 100 years, compared to a global warming potential of 1 per MtCO2.[2]

The Paris Agreement to the UNFCCC (2015) attempts to limit the global average temperature increase to 2°C (3.6°F) above pre-industrial levels, with a preferable goal of 1.5°C (2.7°F), by reducing international GHG emissions. For example, China plans to cut CO2 emissions per unit of GDP by 60-65% relative to the 2005 level by 2030 and to reach carbon neutrality by 2060 (UNFCCC 2016), while the European Union (EU) committed to a target of 55% GHG emissions reduction below the 1990 level by 2030 (UNFCCC 2020). Limiting GHG emissions to remain within a carbon budget[3] is necessary to stabilize human-induced temperature increase. According to the estimates in the IPCC (2021) report, the cumulative human-induced emissions during 1850-2019 were equivalent to 2,390 gigatons (Gt) of CO2 (GtCO2),[4] and resulted in a 1.07°C increase in temperature above pre-industrial levels from 2010 to 2019. The remaining carbon budgets from the beginning of 2020 until achieving net zero emissions are 300-900 GtCO2 for a 1.5°C target and 900-2,300 GtCO2 for a 2°C target. Many countries including the EU, Canada, Japan, South Korea, South Africa, and the United Kingdom have proposed to reach net-zero emissions by 2050 (Climate Action Tracker 2020). The United States

[2] Source: https://www.epa.gov/ghgemissions/understanding-global-warming-potentials#Learn%20why. Last accessed 10/25/2021.
[3] Carbon budget is the maximum amount of cumulative net global human-induced CO2 emissions that would result in keeping global warming to a specific temperature level (IPCC 2021).
[4] 1 GtCO2 = 1 billion MtCO2.

rejoined the Paris Agreement in 2021, aiming to reduce net GHG emissions by 50-52% from its 2005 levels by 2030 (UNFCCC 2021a).

In 2020, parties to the Paris Agreement submitted their updated plans for climate mitigation, known as Nationally Determined Contributions (NDCs). The latest NDCs are insufficient to limit global warming to 2°C above pre-industrial levels (IPCC 2021). The IPCC Sixth Assessment Report also shows that the Paris Agreement goal is still feasible under the very low and low emissions scenarios. Nevertheless, it requires combinations of new and existing technologies and practices, including electrification, hydrogen, sustainable bio-based feedstocks, product substitution, and carbon capture, utilization, and storage (CCUS), which are increasingly expensive. Sanderson and O'Neill (2020) find that the least-cost of mitigation to reach the 1.5°C target was significantly greater than the cost for the 2°C target: 16% of Gross World Product (GWP) by 2070 versus 25% of GWP by 2050, respectively, starting in 2020. The same study also highlights that a later start requires higher costs of emissions reductions: additional annual abatement costs range from nearly $0.6 trillion to more than $5 trillion for 2°C and 1.5°C targets starting in 2020, respectively, compared to the costs of a 1980 start.

In the agricultural context, the Fourth National Climate Assessment (USGCRP 2018) stated that rising temperatures, extreme heat, drought, wildfire, and heavy precipitation are expected to increasingly disrupt agricultural productivity. According to the assessment, the severe U.S. drought of 2012 generated a $14.5 billion loss in agricultural production in the Midwest and the Great Plains. Soon after, the droughts of 2015 and 2017 caused about $7.5 billion in agricultural damages in the United States. Moreover, lower production of field crops, including wheat, led to a scarcity of feed for cattle, which forced ranchers to sell off livestock. Climate change also negatively affects agriculture via changes in water availability, soil erosion, and disease and pest outbreaks. Recent studies find heterogeneous impacts of (short-term) weather variability and (long-term) climate change on agricultural productivity. Sabasi and Shumway (2018) conclude that the warmer temperatures from climate change boost overall agricultural productivity across the United States, while increased precipitation benefits the Southern states and has a mixed impact on the productivity of other states. Njuki et al. (2018) find only mild evidence of an overall decline in U.S. agricultural productivity from weather variability during 1960-2004, due to offsetting positive effects on the Northern Plains and Mountain states and negative impacts on the Pacific region, the Southwest, some parts of the

Midwest, and the Northeast. Ortiz-Bobea et al. (2018) document that agricultural productivity has become more sensitive to high daily summer temperatures, especially in the Midwest due to its specialization in non-irrigated crops. Chambers and Pieralli (2020) report that farmers in the Northeast and the Pacific Northwest benefit from weather variability, while efficiency losses in agriculture affect the rest of the country, especially the Midwest. Plastina et al. (2021) find that weather variability accelerated agricultural productivity growth in most of the states of the Central, Pacific, and Southern Plains regions, having negative effects in four states located in the Northern-most part of the country.

While agriculture is affected by weather variability and climate change, it can also contribute to mitigating climate change through carbon removal and GHG emissions reduction. Agricultural activities accounted for 10% of all U.S. GHG emissions in 2019, with 55% of the emissions stemming from crop cultivation and 39% from livestock production (EPA 2021b). Carbon removal is the process of removing CO2 directly from the atmosphere, which can be achieved through tree restoration and agricultural soil carbon enhancements such as cover cropping and no-till. Emissions reduction is the process of avoiding emissions or capturing them before they reach the atmosphere. Examples of emission reductions technologies for agriculture include nitrogen stabilizers or nitrification inhibitors to avoid the release of nitrous oxide from fertilization applications into the atmosphere, and catchment for energy or destruction of methane gas from manure on hog and dairy operations. The National Academy of Sciences, Engineering, and Medicine (2019) reports that agricultural practices to enhance soil carbon storage can sequester 250 million MtCO2e annually in the United States, equivalent to around 4% of the country's emissions. This potential is particularly relevant to the discussion on how the United States can achieve its GHG emissions reduction target under the Paris Agreement when the technology to generate large-scale and permanent emissions reduction has yet to be developed or is too costly for generalized adoption throughout the economy. In essence, the agricultural sector presents an opportunity to reduce GHG emissions in the short and medium run while large-scale low GHG emissions industrial technologies are developed and adopted. Agriculture can contribute to the Paris Agreement goal by sequestering CO2e and generating tradable tokens ("carbon credits") that can be used by other sectors to compensate for their direct GHG emissions (also called "scope 1" emissions), and their indirect GHG emissions throughout their value chain (also called "scope 3" emissions). When carbon credits are used against scope 1 emissions, they are referred to as carbon offsets, and when they are used against scope 3 emissions, they are referred to as carbon insets.

This article analyzes market-based incentives to generate carbon credits via agricultural practices and trade them under alternative institutional arrangements, highlights the major challenges to scaling-up voluntary agricultural carbon markets in the United States, and describes four possible scenarios for those markets.

Ag Carbon Offsets in the United States

In the United States, demand for carbon offsets generated in the agricultural sector was until recently driven by the derived demand for offsets from three emission-trading systems (ETSs): the Chicago Climate Exchange, the California Cap-and-Trade Program, and the Regional Greenhouse Gas Initiative.[5] In recent years, there has been an explosion of voluntary programs to generate carbon credits, driven mainly by corporate social responsibility pledges from major corporations. This section describes the workings of major carbon programs in the United States.

The Chicago Climate Exchange (CCX)

In 2003, the CCX was established as the world's first and North America's only active voluntary GHG emissions Cap-and-Trade program. It was voluntary in the sense that participants voluntarily chose whether to participate in the CCX, but participants were legally obliged to achieve their annual emission reduction target. The program targeted six GHG emissions – namely, CO2, methane (CH4), nitrous oxide (N2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF6)– included participants from the United States, eight Canadian provinces and sixteen other countries, while incorporating offset projects worldwide. Participants established their own GHG emission baselines and were allocated annual emission allowances that ranged from 99% of their emission baseline in 2003 to 94% of their baseline in 2010. Members who reduced emissions below their targets had surplus allowances, known as exchange allowances, to sell or bank. Members who emitted GHG above

[5] The 2009 American Clean Energy and Security Act proposal intended to establish an emission cap-and-trade program that would cover seven major greenhouse gases from large emitters, petroleum fuels producers and importers, and gas distributors (PEW Center 2009). Using offsets from agriculture and forestry sources would be allowed to meet compliance requirements. However, the bill did not materialize partly due to lack of support in the Senate and the effects of high unemployment stemming from the Great Recession (Weiss 2010).

their targets complied by purchasing CCX Carbon Financial Instrument Contracts (CFICs), each representing 100 MtCO2e.

CFICs included exchange allowances and exchange offsets. Exchange offsets were generated by qualifying offset projects on the basis of sequestration, destruction, or reduction of GHG emissions. All CCX offsets were issued on a retrospective basis with the CFIC vintage applying to the program year when the GHG reduction took place. Projects underwent third-party verifications and verification reports were inspected for completeness by the Financial Industry Regulatory Authority (FINRA). The only agricultural offset projects that qualified for the CCX were based on methane collection and soil carbon sequestration. The minimum scale to trade carbon offsets in the CCX market was 10,000 MtCO2e (equivalent to 100 CFICs), which roughly translates into 25,000 acres in conservation practices (Ribera and McCarl 2009). Consequently, most agricultural projects were managed by aggregators that charged 8-10% of the value of carbon offsets at market price on a yearly basis (Ribera, McCarl, and Zenteno 2009). Forestation, forest enrichment and conservation, and urban tree planting also qualified for generating CCX offsets. The scale required to supply carbon offsets to the CCX severely limited interest from the agricultural sector and small forest landowners.

Although the price of carbon offsets traded in the CCX peaked at $7.40 per MtCO2e in May 2008, it plummeted to 10 cents per MtCO2e in August 2010 (Griesinger 2010). Comfortable baselines, unambitious emission reduction targets, lack of a minimum price on CFICs, and investments in new and cleaner technologies by CCX members contributed to the ceasing of the trading platform in 2010. The problem of the CCX was that the verified emission reductions exceeded the compliance requirement, resulting in an oversupply of carbon offsets (ICE 2011).

Schematically, the failure of the CCX can be illustrated in Figure 1 through a participating firm with a demand curve for CO2e units labeled D, a baseline emission of B units and an annual emission allowance of A units in year t, $A<B$. At a market price of P, the firm would use A units of CO2e. At a market price higher (lower) than P, the firm would use less (more) than A units of CO2e, becoming a net supplier (net user) of CFICs. The following year, the emission allowance drops to A' but after an investment in a cleaner technology the firm has a lower demand for CO2e, D'. The firm unequivocally becomes a net supplier of CFICs: even at a

near-zero market price the firm could supply close to (A'- Q) units of CO2e. When most participating firms become net suppliers of CFICs, the market collapses due to oversupply.

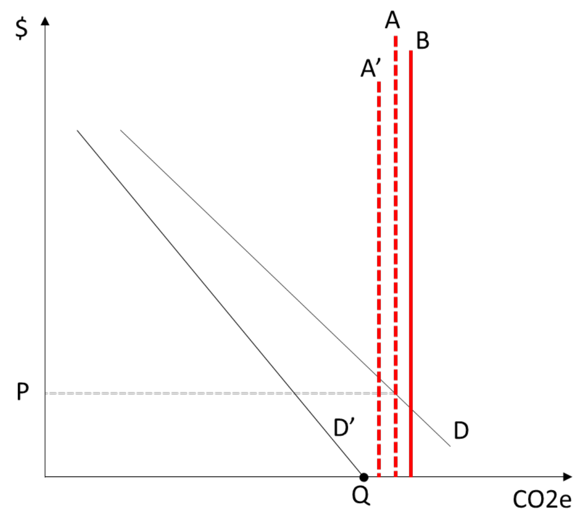


Figure 1. Firm participating in the CCX

The Regional Greenhouse Gas Initiative (RGGI)

In 2005, the RGGI was established as a cooperative effort among the states of Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island, Vermont, and Virginia to cap and reduce CO2 emissions from fossil fuel power plants with an output exceeding 25 megawatts. The compliance obligation started in 2009 with a cap of 170 million MtCO2 and was designed to decline to 82.6 million MtCO2 by 2014, and to be further reduced by 2.5% per year to reach 72.8 million MtCO2 in 2019.[6] However, the cap was adjusted lower in 2014 to account for the surplus of allowances previously accumulated. The adjusted cap amounted to 52 million MtCO2 in 2019. New Jersey left the program in 2012 and rejoined it in 2020 and Virginia did not fully participate until 2021. The adjusted cap increased to 67 million and 91 million MtCO2 in 2020 and 2021, respectively. The regional cap will gradually decrease to total a 30% emission reduction by 2030 relative to the 2020 emission level.

[6] One CO2 allowance in the RGGI is equivalent to one short ton (2,000 pounds) of CO2. For consistency, allowance quantities and prices in the RGGI are reported in metric units using the conversion factor 1 short ton = 0.907185 metric ton.

Allowances are distributed quarterly via regional auctions. The first auction of RGGI allowances took place in September 2008. To prevent extreme allowance price fluctuations, a Cost Containment Reserve (CCR) and an Emissions Containment Reserve (ECR) were implemented in 2014 and 2021, respectively. The CCR is the mechanism to hold allowances in reserve and sell them if allowance prices exceed the trigger price. The CCR trigger price started at $4 in 2014 and climbed to $13 in 2021. The trigger price will increase by 7% annually thereafter. The size of the CCR is 10% of the regional cap each year. The CCR allowances were sold twice in March 2014 and September 2015 at prices of $4 and $6.02, respectively. The ECR allows states to withhold up to 10% of their annual budget if prices fall below the trigger price ($6 in 2021). The ECR trigger price will also increase by 7% annually. Although the trigger price of the CCR and ECR are increasing at the same rate, the 2021 price of the CCR is higher. As a result, the gap between these two trigger prices will widen. In sum, the CCR acts as a ceiling to allowance prices, and the ECR acts as a floor.

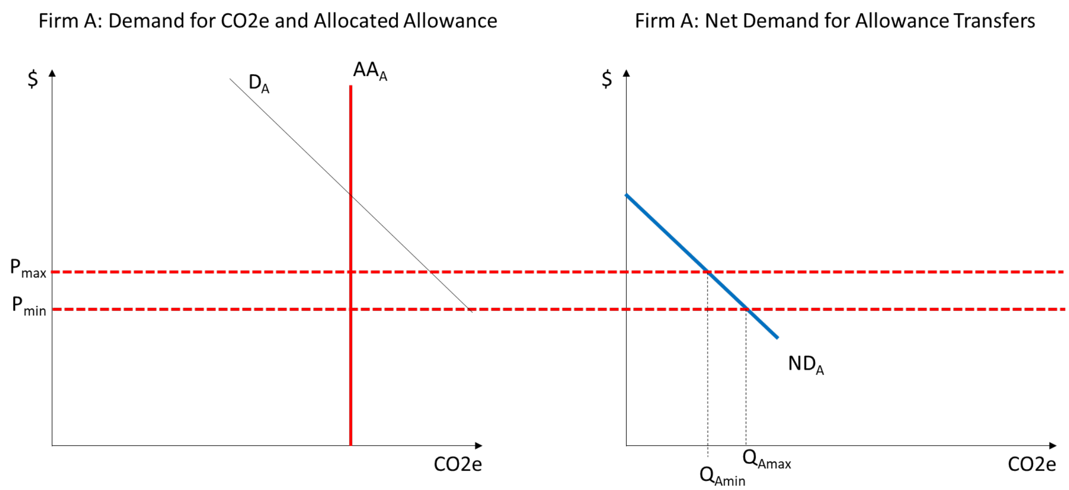
While agriculture and forest emissions are not directly regulated in the RGGI, carbon offsets from methane capture and destruction, and from carbon sequestration through afforestation can be purchased by power plants to be used against their excess CO2 emissions. The use of offsets is limited to 3.3% of a power plant's total compliance obligation. The offsets are also issued on a retrospective basis and require third-party verification. The RGGI CO2 Allowance Tracking System[7] only lists one project as an authorized source of offsets that has produced 48,540 MtCO2e through landfill methane capture and destruction in Maryland since 2017. In comparison, 156,464,910 MtCO2 were auctioned off over the control period 1/1/2018-12/31/2020, at an average price of $6.05 per MtCO2.

According to Acadia Center (2019), the CO2 emissions from power plants in RGGI states declined by 47%, from 121 million MtCO2 in 2008 to 64 million MtCO2 in 2018. Emissions have typically been lower than the cap throughout the program. Accordingly, the RGGI allowances were sold at the reserve price in 11 auctions during 2010-2012 and the allowance prices were below $4.41 per MtCO2 until 2014. The average auction clearing prices increased to $4.87 in 2018, $5.98 in 2019, and $7.07 per MtCO2 in 2020. The allowance price jumped to $10.25 per MtCO2 in the November 2021 auction. Throughout the life of the initiative, CO2

[7] Source: https://rggi-coats.org/eats/rggi/index.cfm?fuseaction=search.project_offset&clearfuseattribs=true. Last accessed 10/11/2021.

offsets were not widely used, representing less than 0.1 million allowances, compared to more than 1 billion allowances sold in auctions.

Schematically (figure 2), the RGGI can be represented with two firms, A and B, facing allocated allowances AA_A and AA_B, respectively, an ECR trigger price of P_{min}, and a CCR trigger price of P_{max}. Firm A has a high net demand for CO2e, ND_A, and would purchase between Q_{Amin} and Q_{Amax} units of CO2e via allowance transfers. Firm B has a low demand for CO2e and would sell or bank between Q_{Bmin} and Q_{Bmax} units of CO2e. The total supply of allowance transfers, NS_T, is the horizontal sum of the net supply from B, NS_B, and the kinked net supply from other sources, NS_O, including the ECR at P_{min}, the CCR at P_{max}, as well as state allowances, and offset allowances over the price range [P_{min}, P_{max}]. The market clears at P* for Q* units of CO2e traded, of which Q_{B*} units are unused allowances from B and Q_{O*} units are from other sources. Firm A uses AA_A+Q* units of CO2e, and Firm B uses AA_B-Q_{B*}, for a total use of $AA_A+AA_B+Q_{O*}$ in the system.



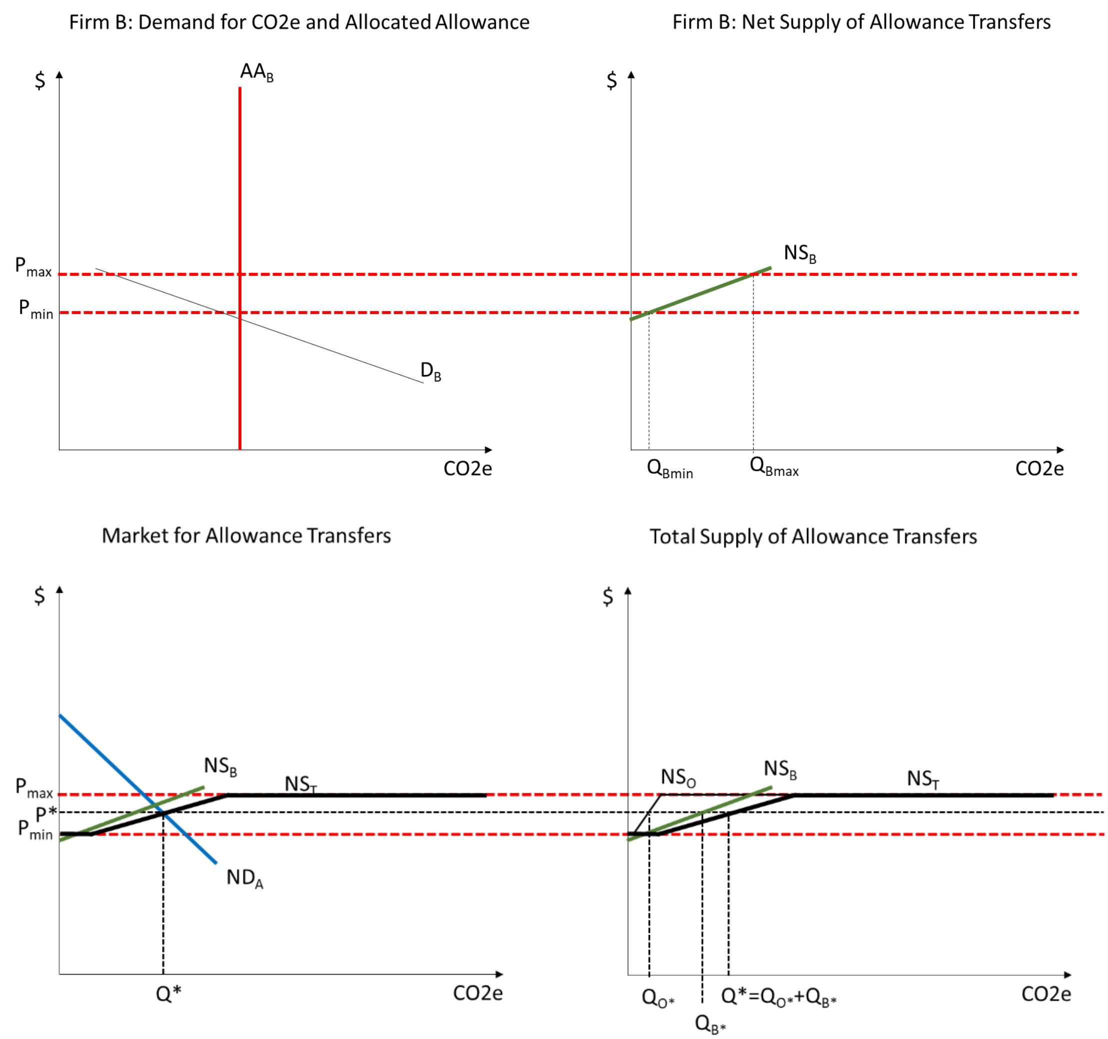


Figure 2. Schematic representation of the RGGI

The goal of an ETS is to induce investments in cleaner technologies by the regulated industries that reduce the demand for CO2e over time. Figure 3 illustrates the decline in the net demand for allowances resulting from an investment by Firm A from ND_A to ND'_A and the associated decline in the market clearing price (from P* to P'*) and quantity (from Q* to Q'*).

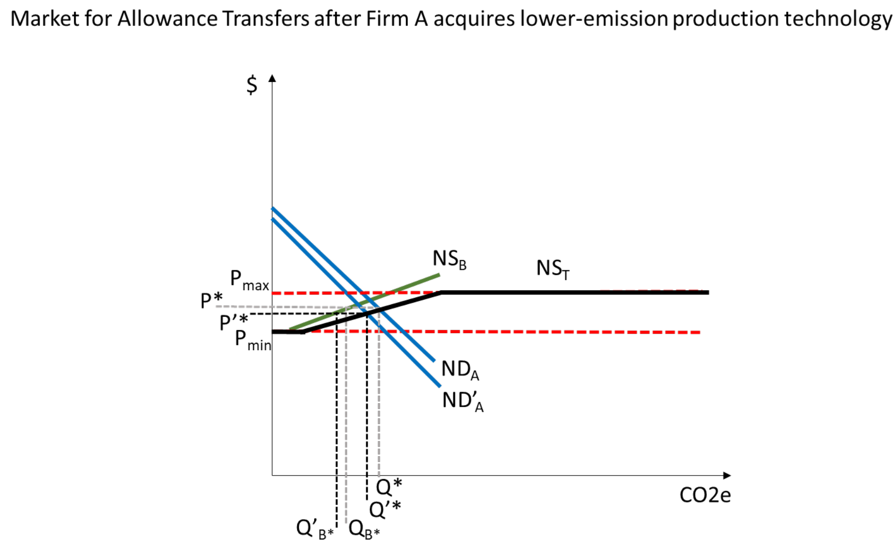


Figure 3. Market effects of an investment in cleaner technologies by Firm A in the RGGI

The California Cap-and-Trade Program (CCTP)

The California carbon cap-and-trade program, launched in 2013, places a cap on GHG emissions from the state's power, industrial, and transportation sectors. Facilities that emit more than 25,000 MtCO2e per year are required to comply with the cap-and-trade program. The program covers three GHGs –namely, CO2, CH4, and N2O – accounting for about 80% of the state's GHG emissions.[8] The California Air Resource Board (CARB) established a cap at 2% below the forecasted 2012 emissions level in 2013, declining at an annual rate of 2% in 2014 and 3% from 2015 to 2020 (CARB 2015). The allowance budget will decrease by 13.4 million MtCO2e from 2021 to 2030, and by 6.7 million MtCO2e per year starting in 2031 (CARB 2019).

California's allowances are distributed via free allocation and auction. Facilities receive free allocation at about 90% of average emissions, updated yearly based on production data. In addition, participants are allowed to bank their unused allowances, subject to holding limits, for future compliance. However, borrowing from future allowances is not permitted. California's program linked with Québec's cap-and-trade program in 2014 and Ontario's program in 2018, although the latter linkage was short-lived. The linkage allows the use of allowances issued in Québec's program to meet compliance obligations in California and vice-versa.

[8] California uses global warming potential conversion factors for CH4 and N2O into CO2e of 25:1 and 298:1, respectively.

Allowances are auctioned-off under two programs. In the Current Auction, allowances for the current year are traded. In the Advance Auction, allowances for the third year into the future are traded, up to a volume equal to 10% of the combined allowance budgets for that year. In 2016 and 2017, auction settlement prices ranged between $10 and $12.73 per MtCO2e. In 2018, allowance prices averaged $14.91 per MtCO2e in the Current Auction and $14.82 per MtCO2e in the Advance Auction. Average prices for both Current and Advance Auctions remained above $16 in 2019 and above $17 in 2020. In 2021, the auction reserve price, which is the minimum price at auction, was set at $17.71 per MtCO2e, and it will increase annually by 5% plus inflation (International Carbon Action Partnership 2021a). In the August 2021 auction, the 2021 vintage allowance price was $23.30 per MtCO2, and the 2024 vintage allowance price was $23.69 per MtCO2.

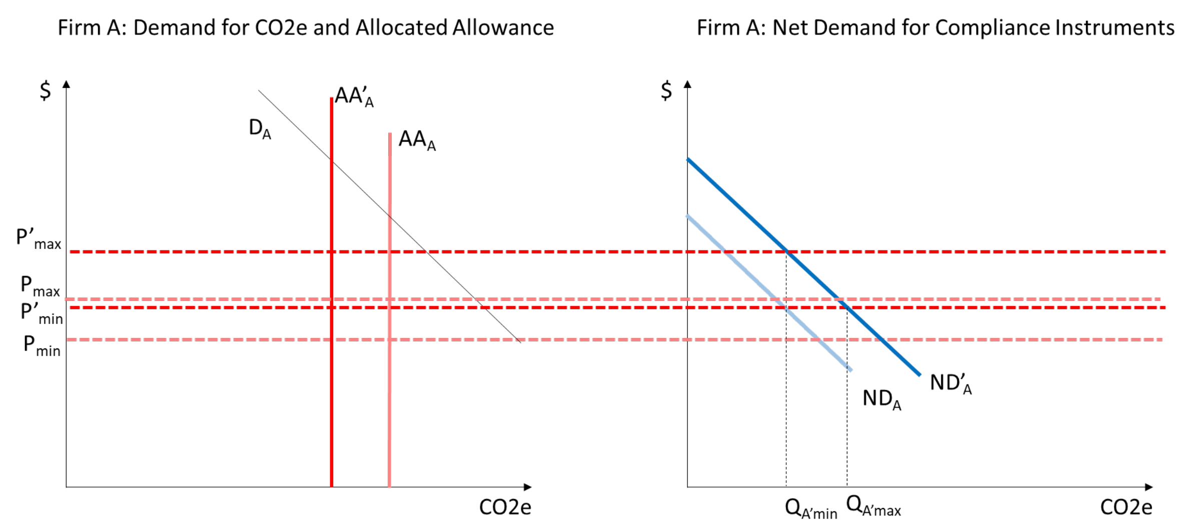
CARB holds a number of allowances in the Allowance Price Containment Reserve ("Reserve") to sell following a quarterly auction when a settlement price is higher than or equal to 60% of the lowest Reserve tier price. In 2021, allowances in the Reserve will be offered at two tier prices: $41.40 and $53.20, and the prices will increase by 5% plus inflation each year. The reserved allowances are also sold in the third quarter of the year before the annual compliance deadline on November 1st.

A regulated facility can use offsets from unregulated sectors within the United States to meet up to 8% of a facility's compliance obligation until 2020, up to 4% in 2021-2025, and up to 6% in 2026-2030. CO2e offsets are issued on a retrospective basis, and the generating project must be verified by an independent third-party accredited by CARB. The program only allows agricultural offsets from capturing of methane from livestock manure and rice (Murray 2015). As of October 12, 2021, total offsets issued throughout the life of the program amounted to 228 million MtCO2e. According to the statistics from CARB, only 3.5% of those offsets came from livestock projects, and none from rice cultivation projects, whereas forestry projects generated 82% of total offsets (via reforestation, improved forest management, and avoided conversion).

California's total GHG emissions decreased by 7.3% between 2012 and 2019. By the end of 2014, the state had reduced GHG emissions by 8.3 million MtCO2e, compared to 2012 levels, after accounting for 12.7 million MtCO2e in offsets. In the second compliance period (2015-2017), emissions declined by 18.5 million MtCO2e, after accounting for 62.7 million MtCO2e in offsets. In 2018-2019, emissions were reduced by 6.3 million MtCO2e, after accounting for 10.8

million MtCO2e from offsets. In addition, 5.8 million MtCO2e from offsets were used to meet compliance in Quebec.

Schematically, California's cap-and-trade system can be represented in a similar fashion to RGGI. The total supply of compliance units, NS_T, is the horizontal sum of the net supply from firm B, NS_B, and the net supply from other sources, NS_O, namely the state Reserve, the Quebec program, and the stock of CARB-verified offsets. Similar to the RGGI, the California cap-and-trade system adjusts regulated prices and allowances through time to induce investments in cleaner technologies. Figure 4 illustrates the effect of declining allowances ($AA'_A<AA_A$ and $AA'_B<AA_B$) and increasing minimum prices ($P'_{min} > P_{min}$) in the absence of new investments. The net demand for compliance instruments from firm A expands from ND_A to ND'_A and the net supply of compliance instruments from firm B contracts from NS_B to NS'_B. Assuming the net supply of compliance instruments from other sources remains unchanged, the market clears at a higher price ($P'^*>P^*$) and more CO2e units are traded ($Q'^*>Q^*$), but the overall CO2e emissions decline by $(AA_A-AA'_A)+(AA_B-AA'_B)-(Q_{O'^*}-Q_{O^*})$, which is positive by construction (positively sloped net supply curve and negatively sloped net demand curve over the relevant range).



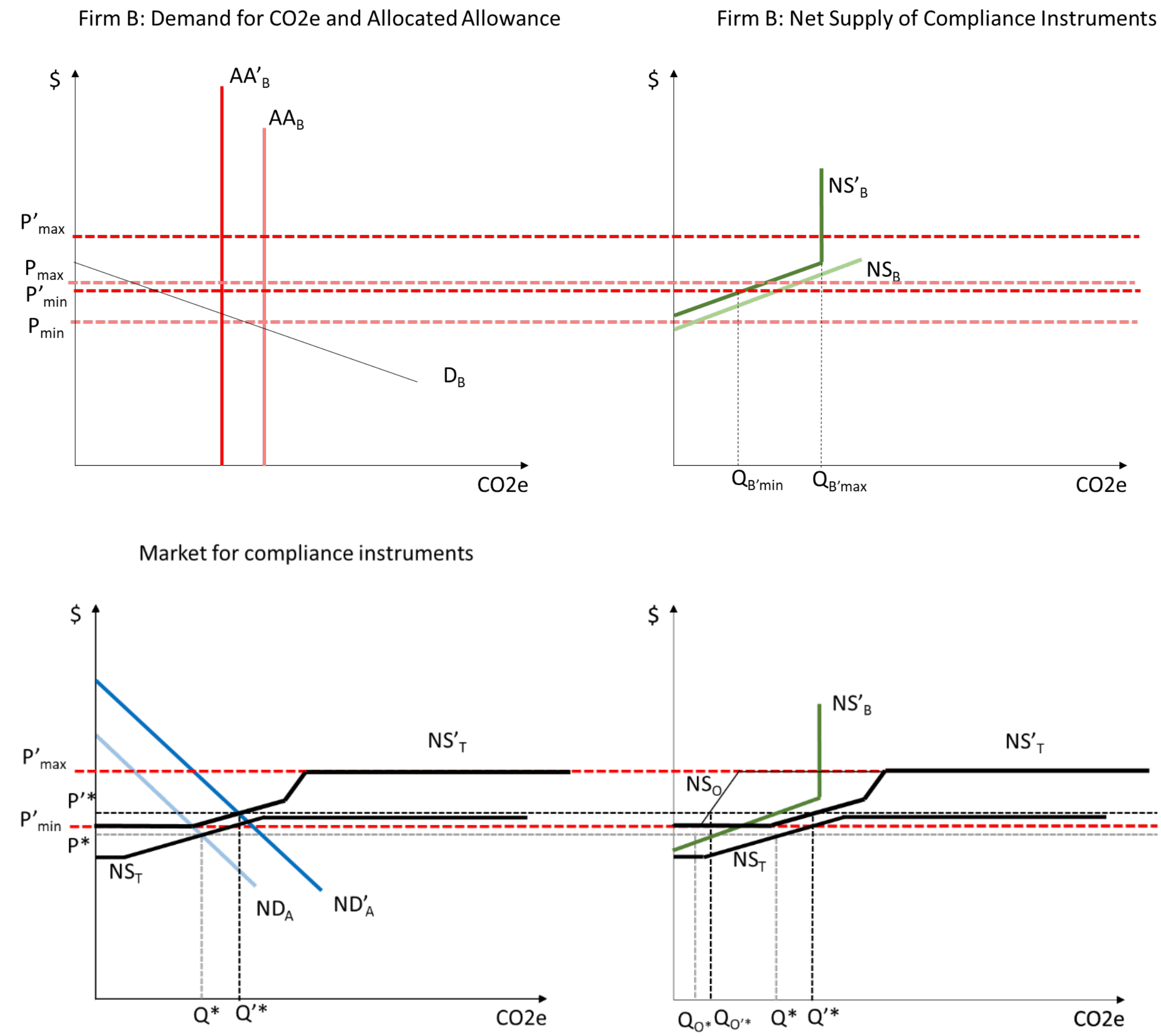


Figure 4. Market change in California Cap-and-Trade system due to changing allocated allowances and regulated prices

Voluntary Ag Carbon Programs

Carbon credits from some agricultural practices, such as soil carbon sequestration, and fertilizer use reductions, currently cannot be used to comply with emission targets in mandatory U.S. carbon markets. The demand for agricultural carbon credits in voluntary markets is expected to stem mostly from the implementation of "net zero" GHG emissions pledges by more than 1,500 companies and 120 nations (Black et al. 2021). Corporations as varied as IBM, JP Morgan Chase, Boston Consulting Group, Dogfish Head Craft Brewing, Shopify, Anheuser-Busch, and Barclays have announced entering into agreements with Indigo Ag to finance the generation of carbon credits. The largest and most detailed announcement so far was made by Microsoft, indicating a commitment to removing 1.3 million MtCO2e from the atmosphere (equivalent to about 11% of the annual emissions from its value chain) through afforestation projects in Peru, Nicaragua and the United States, soil regeneration across U.S. farms, and industrial sequestration of CO2 from the air and injection into the ground where it mineralizes (Jopa et al. 2021). Microsoft specified that less than half of the purchased carbon credits will be certified to officially compensate for its direct emissions (i.e., turn them into carbon offsets), reminding us that certified carbon offsets and non-certified carbon credits will compete for market share in voluntary markets and attract different prices. In addition, since the demand for certified offsets in mandatory markets is driven by regulatory obligations and the demand for voluntary credits is driven by softer targets, the prices for the latter will tend to be lower than the prices for the former.

The current supply of agricultural carbon credits in the United States is very limited, but the recent advent of numerous voluntary carbon programs offering farmers a long menu of options to generate carbon credits (Plastina 2021) could rapidly change that under the right conditions, while generating an additional income stream for program participants. A survey of eleven private voluntary programs indicates that tillage management (reduced till, no-till, strip-till), improved cropping practices (cover cropping, extended crop rotations, and diversification of cropping system-including perennial crops), grazing management, and improved nitrogen efficiency (nitrogen inhibitors, split applications, and in-season applications) are the most commonly accepted farming practices to generate agricultural carbon credits (Plastina and Wongpiyabovorn 2021). Given that only 3.88% and 26.35% of the continental U.S. cropland is planted to cover crops and is in no-till systems (Sawadgo and Plastina, *forthcoming*), [9] respectively, and that nitrogen application rates are above recommended rates in 36% of corn acres, 19% of cotton acres, 22% of spring wheat acres, and 25% of winter wheat acres (Wade et al. 2015), there seems to be a large potential for developing the supply of agricultural carbon credits.

It must be noted that while the USDA administers several voluntary conservations programs – including the Conservation Reserve Program (CRP), the Environmental Quality Incentives Program (EQIP), the Conservation Stewardship Program (CSP), and Conservation

[9] The adoption rate was calculated as area in conservation practices divided by total cropland area. Total cropland includes cropland harvested, crop failure, cultivated summer fallow, cropland used only for pasture, and idle cropland as reported in the U.S. Census of Agriculture (2017).

Technical Assistance (CTA) – none of them are tailored towards fighting climate change or sequestering carbon. However, they indirectly incentivize the sequestration of carbon by supporting conservation activities to improve water and air quality, increase soil health, and reduce soil erosion.[10]

Agriculture Carbon Offsets in Other Countries

The World Bank (2020) reports there are currently 31 ETSs around the world. However, the most important markets for carbon offsets are the Kyoto Protocol, the EU ETS, and the recently instituted Chinese ETS.

The Kyoto Protocol

The Kyoto Protocol, adopted in 1997 and in legal effect since 2005, operationalizes the United Nations Framework Convention on Climate Change (UNFCCC) by committing industrialized countries and economies in transition to limit and reduce GHG emissions in accordance with agreed individual targets (UNFCCC 2008). The Kyoto Protocol set binding emission reduction targets for 37 countries that added up to an average 5% emission reduction compared to 1990 levels over the first commitment period (2008–2012). The Protocol regulates the emissions of six GHG –namely, CO2, CH4, N2O, HFCs, PFCs, and SF6 –, converted into MtCO2e units for compliance purposes.[11] The United States accounted for 36% of the GHG emissions among the committed Parties in 1990, and agreed to a 7% reduction target over the first commitment period. Although the Clinton administration signed the Protocol in 1998, the U.S. Senate never ratified it, making it non-binding for the United States. In December 2012, the Doha Amendment to the Kyoto Protocol was adopted for a second commitment period (2013-2020), with the goal to reduce GHG emissions by at least 18% from 1990 levels. However, the Doha Amendment has not yet been implemented, because less than the minimum 144 instruments of acceptance required for the amendment to enter into force have been filed among the current 192 Parties to the Protocol.

---

[10] Later in this paper we discuss a Congressional proposal that would involve USDA in standards and certification of carbon in agriculture.

[11] According to the IPCC Fourth Assessment Report (https://www.ipcc.ch/assessment-report/ar4/), the 100-year global warming potentials of CO2, CH4, N2O, HFCs, PFCs, and SF6 are, respectively, 1, 25, 298, 12-14800, 7390-17340, and 22,800.

Parties with commitments under the Kyoto Protocol in 2008-2012, usually called Annex I Parties, had to meet their targets primarily through national measures, but they could make progress towards their goals by trading emission permits (UNFCCC 2021b). Each Annex I Party was assigned a number of emission units called "assigned amount units" (AAUs). Countries with unused AAUs could sell them to other countries with emissions above their targets. The Protocol also allowed three other mechanisms to achieve commitments: removal units, emission reduction units, and emission reductions.

Investments in activities related to forestry, afforestation, reforestation, deforestation, revegetation, forest management, cropland management and grazing land management[12] that resulted in additional net removals of GHG from the atmosphere could be used to generate removal units (RMUs) to offset emissions under the Protocol.

Under the Joint Implementation mechanism, an Annex I Party could invest in an emission reduction or emission removal project in another Annex I Party to earn emission reduction units (ERUs) that would count towards its Kyoto target. This mechanism would benefit the host Party through foreign investment and technology transfer.

The Clean Development Mechanism (CDM) allowed Annex I Parties to invest in emission reduction projects in developing countries and earn saleable certified emission reductions (CERs) that could be used to offset emissions and meet the Kyoto target. The CDM was the first global, environmental investment and credit scheme of its kind, providing a standardized emission offset instrument, the CER.

The Kyoto Protocol creates a monitoring, review and verification system for AAUs, RMUs, ERUs, and CERs, jointly referred to as "Kyoto compliance units," as well as a compliance system to ensure transparency and hold Parties accountable. Countries have to monitor actual emissions and keep precise records of the executed trades to comply with the Protocol. Reporting requirements include annual emission inventories and national reports at regular intervals. A network of registry systems tracks and records transactions by Parties under the mechanisms, and the United Nations Climate Change Secretariat keeps an international transaction log to verify that transactions are consistent with the rules of the Protocol. A compliance system ensures that Parties meet their commitments and works with them to address emerging challenges. Furthermore, each Annex I Party is required to maintain a *reserve* of Kyoto

[12] These activities are categorized as land use, land-use change and forestry (LULUCF) activities.

compliance units in its national registry equivalent to at least 90% of its AAUs or five times its most recently reviewed history, whichever is lowest (UNFCC 2021b).

During the first commitment period (2008-2012), total emissions from Annex B Parties (i.e., Annex I Parties that ratified the Protocol) declined by 22.5% from their base year (1990 for most countries). Total AAUs for the whole period represented 57,642 million MtCO2e, while 19,621 million MtCO2e were assigned solely to the EU. Total GHG emissions were 18.9% lower than the assigned amount for all Annex I Parties (46,722.9 million MtCO2e), and 4.1% lower for the EU (18,822.3 million MtCO2e) (UNFCCC, 2015). According to Aldrich and Koerner (2012), trading of AAUs was usually bilateral with confidential prices. A trade between Poland and Ireland occurred at €10 per AAU in December 2008, which was below the €15–20 price for an EU AAU in the fourth quarter of 2008. At the end of the first compliance period, Annex B Parties held 48,745.6 million AAUs, 287.5 million ERUs, 537.2 million RMUs, and 325.5 million CERs (UNFCCC,2013).

Schematically, the market for Kyoto compliance units can be represented by a net demand ND_A for CO2e from Annex B Party A (including its *reserve* amount), facing a kinked total net supply of NS_T, comprised of the supply of unused AAUs from Annex B Party B (after subtracting its *reserve* amount), NS_B, and the net supply of other compliance units, NS_O, including RMUs, ERUs, and CERs. The market clears at P* for Q_{A*} compliance units, comprised of Q_{B*} units from Party B and Q_{O*} units from other sources. Total regulated CO2e emissions in the system, assuming countries maintain 90% of their AAUs in *reserve*, amount to $0.9(AAUs_A+AAUs_B)+ Q_{O*}$.

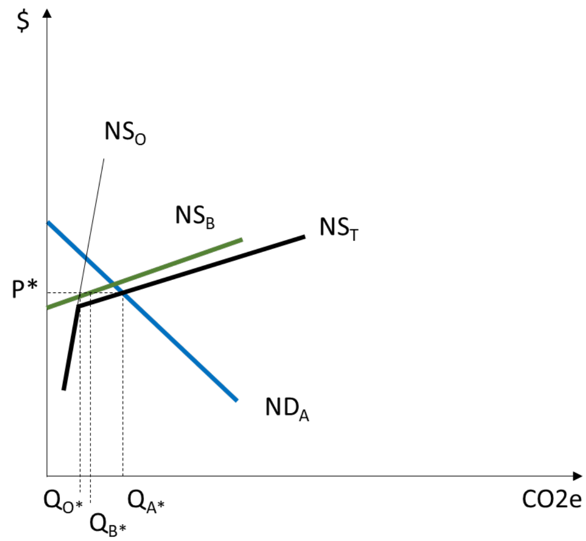


Figure 5. Market for Kyoto compliance units

The EU ETS

The largest carbon market is the EU ETS, which is a mandatory cap-and-trade system covering almost 5% of the world's annual GHG emissions (World Bank 2020), and includes all EU members states.[13] The EU ETS currently covers three GHGs –namely CO2, N2O, and PFCs– from power generation, energy-intensive industry, and commercial aviation sectors. The EU has demonstrated a commitment to make the cap on emissions binding, introducing reforms to the ETS that absorbed the oversupply of EU Allowances (EUAs) during the Great Recession of 2008-2009 and prevented a collapse of the EUA price (Wongpiyabovorn, Plastina, and Lence 2021).

During phase I (2005-07) of the EU ETS, futures prices of EUAs fluctuated dramatically, from €20 to less than €1 per MtCO2e, due to an excess of freely allocated EUAs (Raymond and

[13] Following Brexit, the UK implemented its own UK ETS as of January 2021. Switzerland, which is not an EU member state, has its own ETS tied to the EU ETS since January 2020.

Shively 2008). According to European Commission (2021a), freely allocated EUAs accounted for about 90% of all EUAs in the second compliance period (2008-2012), and auctions of EUAs started in 2012 via the Intercontinental Exchange (ICE) and the European Energy Exchange (EEX). Trading volumes rose from 321 million EUAs in 2005 to 3.1 billion in 2008, and 7.9 billion in 2012. In 2012, auction prices averaged €6.18 and €6.95 per MtCO2e in the ICE and the EEX, respectively (ICE 2021; EEX 2021), and EUA futures prices averaged €7.42 per MtCO2e. The EUA prices in phase II were low because actual emissions were lower than expected as a consequence of the Great Recession. The average daily trading volume of EUA futures in the ICE was 217 contracts during phase I and 3,312 contracts during phase II.

Starting in 2013, freely allocated EUAs are no longer calculated on the basis of annual production levels by power plants. In phase III (2013-2020), 57% of used allowances came from auctions and the rest came from freely allocated EUAs based on activities in the base year (International Carbon Action Partnership 2021b). The annual cap decreased at the rate 1.74%, leading to rising allowance prices. Auction clearing prices rose from €5.70-€5.79 per MtCO2e in 2017 to €15.34-€15.91 in 2018 and €23.89-€24.42 in 2020. Similarly, ICE futures prices for EUAs increased from €5.92 per MtCO2e in 2017 to €25 in 2020. Although EUA spot and futures can be traded in both ICE and EEX, ICE is a larger secondary market, accounting for 97% of trading volume in 2019. In 2020, ICE EUA futures traded 32 million MtCO2e, and ICE spot EUA traded 2.5 million allowances on a daily basis (ICIS 2020).

The EU ETS is currently in phase IV (2021-2030), with a goal to reduce emissions by at least 40% compared to the 1990 level, and a cap on emissions that decreases by 2.2% per year. The annual reduction of EUAs has substantially driven up the EUA price to around $60 per EUA in September 2021 (Wongpiyabovorn, Plastina, and Lence 2021).

EU Member States also have binding annual GHG emission targets for sectors of the economy that fall outside the scope of the EU ETS, namely road transport, heating of buildings, agriculture, small industrial installations and waste management. These non-ETS sectors generate about 60% of the EU GHG emissions and have a 29% target emission reduction by 2030, compared to 2005 levels. Annual targets are distributed among EU Member States according to the Effort Sharing Regulation (ESR) adopted in 2018, based on relative gross domestic product per capita and cost-effectiveness. Target emission reductions by 2030, in relation to their 2005 levels, range from 0% for Bulgaria to -40% for Luxembourg and Sweden (European Commission 2021b). In order to provide flexibility in compliance, the ESR allows for banking, borrowing and buying and selling of allocations between Member States (within certain limits). It also allows seven Member States (Austria, Belgium, Denmark, Finland, the Netherlands, Malta and Sweden) and Norway to use EUAs (from the EU ETS) for offsetting 2% of the emissions in their non-ETS sectors, and two Members States (Ireland and Luxembourg) and Iceland to do the same for up to 4% of their non-ETS emissions. The total maximum amount for all eleven eligible countries is limited to 107 million MtCO2e over the period 2021-2030. Another flexibility mechanism to achieve target emission reductions in the non-ETS sectors allows for the use over 2021-2030 of up to 262 million MtCO2e from offsets generated in the land use sector. If a Member State does not meet its annual obligation, taking into account the use of flexibilities, the shortfall is multiplied by a factor of 1.08 and the result is added to the following year's obligation as a penalty (European Commission 2021b).

A recent proposal by the European Commission (2021c) intends to expand the EU ETS to include national targets for emission reductions from non-ETS sectors, starting in 2025. The proposal would increase the target emission reduction by 11 percentage points to -40% by 2030 and provide a more flexible mechanism to achieve the target through the EU ETS. It would also integrate the policy framework covering activities related to agriculture, forestry, and land use (AFOLU) under one climate policy tool beyond 2030; increase the net carbon removals target from forestry and land use by 15% to -310 million $MtCO_2e$ for the EU by 2030; include non-CO_2 agricultural emissions such as those from fertilizer use and livestock in the calculation of GHG emissions from AFOLU; and aim for reaching climate neutrality in AFOLU by 2035.

The Chinese ETS

China opened a national carbon market on July 16, 2021. Only coal- and gas-fired power plants, which account for 10% of global GHG emissions and 40% of China's carbon emissions (International Carbon Action Partnership 2021c), are currently subject to the emissions cap due to the difficulty in measuring and monitoring emissions in other industries. Free allowances are distributed to power plants, with the current price at $8 per $MtCO_2e$ emissions (Buckley 2021). Additionally, offsets from the China Certified Emissions Reduction (CCER) program can be used against up to 5% of their verified emissions (International Carbon Action Partnership 2021c). The CCER projects cover renewable energy, biogas utilization, and other activities. According to a report from the Environmental Defense Fund (2020), 1,047 CCER projects have been registered and are expected to reduce emissions by 139.6 million $MtCO_2e$ per year. Among the registered projects, 15 projects are forestry-related, including one that has already generated registered carbon offsets. No agricultural projects have been registered as of April 2020.

Carbon Taxes

While ETSs limit GHG emissions through maximum allowances and minimum prices, governments can also generate disincentives to emit GHG via taxation. Carbon taxes can be imposed on domestic production to incentivize GHG emission reductions in the country levying taxes, or on imports of products with high GHG footprints to incentivize emission reductions in the exporting countries.

Domestic carbon taxes

Carbon taxes directly set a price on emissions and the market determines the equilibrium emissions level (Raymond and Shively 2008). The World Bank (2020) lists 30 carbon taxes around the world, with 18 countries and 3 regions exploring the joint implementation of carbon taxes and complementary ETSs.

Finland was the first country to implement a carbon tax in 1990. Another 19 countries in Europe, as well as Japan, Mexico, Chile, and Canada followed suit. As of April 1, 2020, the highest carbon tax rate was €119 per MtCO2e in Sweden, while the lowest rates were less than €1 in Poland, Ukraine, and Mexico (World Bank 2020). Each country's carbon tax covers different types of GHG emissions. For instance, the carbon tax in Spain only applies to fluorinated gases, which account for 3% of its total GHG emissions. In contrast, Norway has a wide-ranging carbon tax that covers more than 60% of its GHG emissions (Asen 2021; World Bank 2020). Mexico, Colombia and South Africa have complementary ETS and carbon taxes and allow the use of verified carbon credits issued by voluntary programs as a means to comply with carbon tax obligations (World Bank 2021). Governments typically use revenue from carbon taxes to finance the uptake of cleaner power and transportation technologies, and climate change mitigation strategies.

In the United States, the Joint Committee on Taxation and the Congressional Budget Office projected that a broad-based carbon tax starting at $25 per MtCO2e in 2017 and rising at 2% more than inflation would have raised $1 trillion over its first decade (Congressional Budget Office 2016). Projections by the Brookings Institution (2019) suggest that a $25 per MtCO2e tax that rises by 1% per year would reduce emissions by 17-38% by 2030, compared to 2005 levels. A $50 per MtCO2e tax increasing by 5% per year causes GHG emissions to decline by 26-47% relative to 2005 levels, equivalent to up to 90% of the reductions needed to achieve the U.S. goal under the Paris Agreement. Resources for the Future (2021) projects that a $15 per MtCO2e tax levied on oil and gas producers starting in 2023 and increasing by 5% per year would reduce emissions to about 40% of the 2005 levels by 2030. Under current policies, the U.S. is projected to reduce emissions by 20-26% by 2030, compared with 2005 levels (Pitt et al. 2021), well below the U.S. target of almost halving GHG emissions by 2030 in the Paris Agreement. However, a carbon tax on domestic production does not seem to be in the agenda of policy-makers in the United States.

Schematically, the effect of an excise carbon tax can be explained with figure 6. Prior to the tax, in the absence of regulated or voluntary caps on emissions, the price for GHG emissions is null. In equilibrium, a firm with demand function D will use Q units of CO2e. After the imposition of a tax of T dollars per unit of CO2e, the firm will use Q' units of CO2e, resulting in a reduction of GHG emissions of Q-Q', and tax revenues of T×Q'.

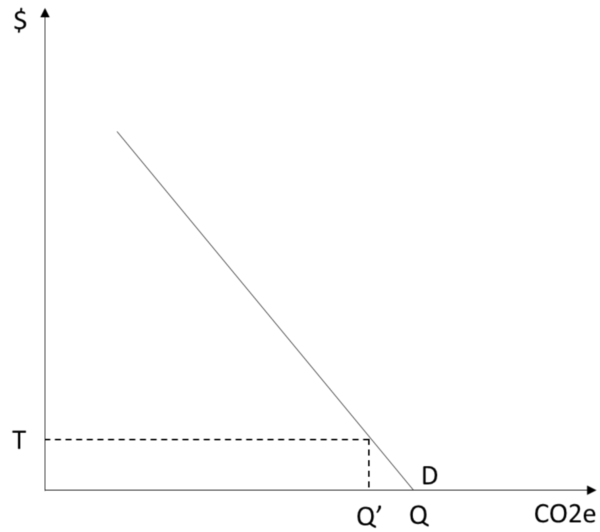


Figure 6. Effect of a carbon tax

Carbon border adjustment mechanism

On July 14, 2021, the European commission proposed a EU carbon border adjustment mechanism to tackle emissions leakage by taxing imported goods from countries that do not tax GHG emissions in the same way as the EU. Emissions leakage could occur when industries relocate from a country that imposes emissions constraints to another country that has less restrictive climate change policies, and total emissions increase. Aichele and Felbermayr (2015) found evidence of carbon leakage from an 8% increase in sectoral carbon imports in the countries that committed to the Kyoto Protocol, relative to the case without the accord. The carbon border adjustment mechanism would prevent polluting industries from relocating production outside Europe to avoid the emissions limits. The levy would target aluminum, cement, fertilizer, power, steel, and iron industries (Toplensky 2021).

On July 19, 2021, U.S. Democratic lawmakers proposed a carbon border tax for imported petroleum, natural gas and coal, and other imported products that have a large carbon footprint such as aluminum, steel, iron, and cement. The border tax would apply to about 12% of U.S. imports, and would raise between $5 billion and $16 billion per year, starting in 2024. However, the proposal faces steep resistance in Congress (Friedman 2021).

Challenges to Voluntary Ag Carbon Markets

As many countries and corporations around the world accelerate GHG emissions reduction and aim for being carbon neutral, demand for carbon credits will likely increase. However, since carbon credits and offsets are credence goods,[14] scaling up voluntary agriculturalcarbon markets faces multiple challenges, both from the demand and the supply side.

Demand-side Challenges

Issues that can undermine a market for credence goods are well known in economics. Where labels or certification are used to verify a claim on a credence good, markets fail in the presence of difficult to verify claims; a misunderstood or poorly worded label; lack of clear, consistent and uniform guidelines across certifying parties; lack of trust on certifiers (especially when these are not independent third-parties); and label proliferation (the existence of too many labels in a market or on a good leading to confusion about competing claims). Economists have examined these issues in other areas, so much is already known. Giannakas (2002) and Bonroy and Constantatos (2015) examined information asymmetries in the organics markets concluding that a viable market must have viable certification and undermining of the labels could do great damage to the industry. When Bithas and Latinopoulos (2021) elicited consumers' willingness to pay for carbon sequestration in a stated preference experiment of forest product consumption, they asserted to the respondents that the carbon truly was being sequestered, something that may only be inferred in a real market. In the absence of verification, adverse selection (Akerlof 1970) may lead to a market failure of a carbon sequestration claim. As is seen in the variety of 3rd-party certifiers in the carbon sequestration market today, the need for verification is already understood.

[14] Credence goods are goods with qualities that cannot be ascertained by consumers even after consumption (Darby and Karni 1973). A carbon credit or offset based on a claim that GHGs have been sequestered from the atmosphere or emissions have been avoided through certain processes is a credence good.

Consumers would likely not trust the manufacturer to correctly self-report carbon sequestration because it is arduous for consumers to detect whether a firm's suppliers follow carbon sequestration processes (search costs to verify a label are indeed large barriers, Teisl and Roe 1998). Certification agents (public or private) who specialize in such detection are necessary in cases where the labels signal the production methods, regional sourcing, environmental impacts, safety or quality of a good. The absence of the label for a desirable attribute creates a "lemons problem" (Akerlof 1970) where consumers who have a higher willingness to pay for a carbon credit cannot detect the attribute in the absence of a label and will not believe it in the absence of certifier credibility. The market will fail not because of a lack of demand but because of a lack of information. Caswell and Mojduszka (1996) and Marette and Roosen (2011) delved into this issue in the case of food labeling; Crespi and Marette (2003, 2005) examined the issue in the case of public labels and eco labels, respectively, while Roe and Sheldon (2007) and Roe, Teisl and Deans (2014) examine the literature on credence good labels in general.

Without government-backed standards, we should expect questionable carbon claims and an increase in competing claims, so-called "label proliferation." Kiesel and Villas-Boas (2013) and Marette (2014) delve into this issue, which arises when products and markets contain multiple labeled attributes. The concern here is a different type of market failure where consumers become so overwhelmed by competing messages that they lower their willingness to pay for an attribute because of the noise. Label proliferation leads to a "crowding out" of desirable attributes similar to Akerlof's lemons problem. In short, in the absence of standards and verification, buyers of carbon credits and the downstream consumers of credit buyers' products or services may be reticent to assign much value to a GHG sequestration or emission reduction claim.

Another challenge in voluntary carbon markets is that entities promising net zero emissions or specific GHG emissions targets usually place the target date a decade or more into the future. While such behavior makes sense from a planning perspective, it also allows those entities to commit some investments at the time of the initial announcement, and then postpone further investments until near the target date. The disconnect between long-term voluntary goals and short-term annual purchases of carbon credits or investments in carbon credit generation could result in pent-up demand in years of large announcements, followed by years of low demand and prices, and again high-demand in target years. Such cyclicality, combined with the multi-year processes required to produce agricultural credits, could generate incentives to discontinue carbon sinking practices and disrupt the supply of carbon credits prior to the target years.

Although not currently a barrier to the development of agricultural carbon markets, the carbon footprint of the whole system involved in generating carbon credits, including issuance and tracking of the serial numbers for each project in the carbon registries, along with financing projects and trading credits, could become a concern for consumers of carbon credits or the end products or services where carbon credits are applied to reduce their carbon footprint. For example, West and Marland (2002) found that the carbon stored in soil organic matter by reduced-tillage is offset by the GHG emissions into the atmosphere through increased production, transportation, and application of chemicals. Another example is that an afforestation program under carbon markets in a specific region could result in net losses in stored carbon because of the intensification of agricultural production in unregulated regions (Haim, White, and Alig 2016). Carbon programs that use energy-intensive accounting and verification systems (e.g., Blockchain technology) might generate net positive carbon emissions, and could become less desirable than carbon programs with a smaller GHG footprint.

Supply-side Challenges

Related to the credence attribute of carbon credits, farmers may be reticent to change production practices in order to generate carbon credits of unknown value. Likewise, in the face of an uncertain market, lending institutions may be reticent to fund producers who possibly need specific assets for the production methods applied in the generation of carbon credits.

Accurate measurement and verification of carbon credits from agricultural and forestry activities are typically difficult and costly (van Kooten 2008). Collecting soil sample and measuring soil organic carbon is currently the most accurate way to measure the amount of carbon stored in the soil, but it is too costly and time-consuming to be widely used (Castagné et al. 2020). Data collection from satellite mapping may provide an accurate calculation of soil carbon at a lower cost. However, this method is still lacking in terms of roughness, soil moisture, and vegetation cover, which would lead to less robust estimation (Angelopoulou et al. 2019).

Voluntary carbon programs follow different protocols based on different models to calculate how much carbon is sequestered through the implementation of agricultural practices

(Plastina 2021). For example, while Cibo Impact uses the System Approach to Land Use Sustainability (SALUS) model to calculate carbon credits, Nori and the Soil and Water Outcomes Fund use the COMET-farm model, and Ecosystem Services Market Consortium (ESMC) uses the DeNitrification-DeComposition (DNDC) model and the Operational Tillage Information System (OpTIS) model to calculate carbon credits. The complexity involved in comparing potential carbon credits generated by one specific practice in a particular farm across programs could discourage objective technical comparisons of programs and result in farmers choosing programs with the best customer service rather than the highest potential profitability.

Non-additionality is one of the major risks making conservation programs cost-ineffective. Agricultural conservation practices yield additional environmental gain only if they would not have been adopted without payment. Estimating additionality for selected agricultural practices, Claassen et al. (2018) conclude that the adoption of three off-field structural practices (filter strips; riparian buffers; and field borders) and the elimination of fall application of nitrogen fertilizer were highly additional, while the adoption of conservation tillage was only moderately additional. Sawadgo and Plastina (2021) estimate that cover crops were moderately additional and that over half of farmland in cost-share programs funded cover crop acreage would not have been planted without payments. The eleven voluntary agriculture carbon credit programs analyzed by Plastina and Wongpiyabovorn (2021) require additionality to generate a carbon credit. However, not all programs require that farmers change their production practices since programs use a wide array of benchmarks to determine what is additional or different: some programs require a change of practices with respect to past practices on the same field, while others require that practices in the field be different from common practices in the area (even if the same practices have been implemented for many years in the field under consideration).

Permanence is another major driver of carbon credit quality. Generating high-quality credits with long-lived carbon storage in the soil is a costly process, due to the required changes in farming practices that sometimes reduce productivity –even if temporarily-, and the costs to verify and certify the carbon sequestration. For example, no-till could reduce crop productivity, particularly in cooler and/or wetter climatic conditions due to the surface residues and lower soil temperatures (Ogle, Swan, and Paustian 2012). According to Gramig and Widmar (2018), farmers in Indiana who have never adopted any conservation tillage or no-till would require almost a $40 per acre increase in net revenue to implement no-tillage, while individuals who previously used conservation tillage would be willing to adopt with no payment. They also found that an additional $10.57 per acre is needed to enter the program with a multi-year contract that does not allow them to change their tillage practices during the contract term. Having a carbon project certified to generate high quality carbon credits according to the Gold Standard registry can cost $5,000 in one-time validation fees and $3,500 per year in annual verification and registry fees (Gold Standard 2021). Furthermore, Plastina and Wongpiyabovorn (2021) report that when contracted practices are temporarily discontinued due to factors external to the farm (e.g. weather), some voluntary agriculture carbon programs impose penalties associated with skipping payments for the discontinued practices until reinstated (Soil and Water Outcomes Fund, CIBO Impact) or until additional gains in carbon sequestration are observed (ESMC, Indigo), and at least two initiatives do not have any penalties for permanent dis-adoption (Gradable, Bayer).

In the present environment of burgeoning agricultural carbon programs, little attention is paid to the potential effects of alternating adoption, opportunistic adoption, and partial adoption on total area under conservation practices (Pannel and Claasen 2020), let alone their limiting effects on the development of voluntary carbon markets. Carbon reversal from dis-adoption of conservation practices can occur when a participant of a carbon program stops using the contracted practice when the contract expires. Jackson-Smith et al. (2010) studied a single watershed in Utah during 1992 – 2006 and found that 66% of crop production practices implemented were still maintained in 2007, and 32% of the practices that were discontinued were driven by farmers exiting farming or selling land for nonfarm development. Using county-level data from the 2012 and 2017 US Censuses of Agriculture, Sawadgo and Plastina (forthcoming) evaluate regional patterns of adoption and disadoption of conservation practices in the United States. They estimate that national disadoption rates in cover crops and no-till averaged 15.60% and 39.38%, respectively, between censuses. Plastina and Sawadgo (2021) report that 11% and 33% of the counties in Iowa, Illinois, and Indiana disadopted cover crops and no-till, respectively, reducing their areas in those conservation practices by 25% and 13% between 2012 and 2017. If these percentages are indicative of the probability that farmers participating in voluntary carbon programs could temporarily discontinue contracted practices and trigger penalties from carbon programs, those findings suggest that farmers planting cover crops and using no-till would face non-trivial probabilities of being penalized over the life of a multi-year carbon contract.

Even within a credible verification and certification system mitigating uncertainty in the conversion of agricultural practices into carbon credits, suppliers of agricultural carbon credits will face competition from other suppliers of carbon credits generated in forestry, geological carbon sequestration, ethanol production with carbon capture and sequestration, landfill methane capture and destruction, and multiple other sources. The quality of credible agricultural carbon credits, dependent mostly on the degree of additionality and permanence of the carbon sequestration, will play a critical role in the determination of payments received by farmers (via direct sale of credits to end users and brokers, or indirectly via carbon programs that sell credits to investors).

The cyclicality in demand for carbon credits due to strategic behavior by entities with voluntary GHG emissions targets could, as explained above, generate price signals in the early stages of the cycle incentivizing farmers to enroll in multi-year carbon programs, generating an oversupply of credits and a decline in credit prices when demand drops in the middle of the cycle.

Although outside the context of carbon programs, multiple studies have examined barriers to adoption of conservation practices (e.g., Prokopy et al. 2019, 2008; Ranjan et al. 2019), suggesting that a diverse combination of economic and agronomic factors, social norms, perceptions of government programs, farm characteristics, land tenure factors, and knowledge-related factors can be pose barriers to conservation adoption (Nowatzke and Arbuckle 2018; Prokopy et al. 2008, 2019; Ranjan et al. 2019).

A further barrier to participation in carbon programs is lack of transparency in the price discovery mechanism for participating farmers. Farmers and ranchers interested in carbon programs are currently being offered anywhere between $10 to $40 per acre to implement practices that will generate carbon credits, but prices will be subject to market fluctuations beyond pilot programs (Plastina and Wongpiyabovorn 2021). In March 2020, the CME Group began trading CBL Global Emission Offset (GEO) futures contracts. The aim of these futures contracts is to help manage risk in carbon prices and establish a global pricing benchmark for the voluntary emissions offset market (CME Group 2021a). In August 2021, the CME Group also started trading futures contracts for offsets generated from agriculture, forestry, and other land use, called Nature-Based GEO (N-GEO). To ensure the transparency of N-GEO futures, only the offsets from Verra's Verified Carbon Standard for Agriculture, Forestry, and Other Land Use projects and/or the Climate, Community, and Biodiversity Standards are accepted for trading (CME Group 2021b). As of August 20, 2021, the average prices of GEO and N-GEO futures were $5.11 and $7 per metric ton of CO_2e, respectively. Trading volumes in August 2021 averaged 198 and 503 contracts per day (equivalent to 0.2 and 0.5 million metric tons of CO_2e) for GEO and N-GEO futures, respectively, with open interest of 835 and 6,092 contracts at the end of the month. The lack of "hard" caps on GHG emissions in voluntary programs and the small number of carbon credits traded, along with the cyclical pattern of demand for carbon credits, and the resulting lack of volatility to attract speculators that inject liquidity in the market are major reasons to be skeptical about the ability of GEO and N-GEO futures to serve as a pricing benchmark for voluntary agricultural offsets (Wongpiyabovorn, Plastina, and Lence 2021).

Conservation practices can not only sequester carbon and reduce GHG emissions, but they can also benefit farmers by reducing soil erosion, improving water infiltration, soil water storage, and soil quality. In addition, cover crops and proper nutrient management could improve water quality by reducing nitrate leaching and phosphorous runoff to nearby water bodies. However, the co-benefits from adopting these practices are uncertain and take time to develop. For example, the adoption of no-till/strip-till takes more than 5 years to yield reduced soil erosion and sediment loss to water and wind, and an increase in water-storage capacity (Toliver et al. 2012). If policy-makers choose to incentivize farmers' participation in carbon and ecosystem services programs through subsidies or cost-share programs, it is important to keep in mind that uniform payments across geography and/or based on adopted practices are not cost-effective to deliver desirable environmental outcomes (Khanna 2017). Secchi and Jones (2021) propose that government subsidies be used to support long-term or permanent practices, such as land retirement and reforestation due to their associated water quality and habitat co-benefits, rather than investing in carbon capture and storage projects at ethanol plants.

Finally, as long as buyers of agriculture carbon credits perceive differences in the quality of credits generated through alternative protocols, it can also be expected that some programs will gain market share and some will exit the market, affecting systemic risks for farmers and credit buyers (Plastina and Wongpiyabovorn 2021). The risk to farmers could be partially mitigated through the standardization of equivalences for carbon farming practices across initiatives, and the introduction of transferable partial and full credits across protocols. However, the risk of a shorter-than expected permanency of a carbon credit triggered in the event that a program exits the market and farmers who sold credits through that program discontinue the practices before the expiration of the retention period is only partially mitigated in a few programs through retained carbon credits. Credit reversals are a liability for which there is no insurance policy currently available.

A Way Forward for Voluntary Ag Carbon Programs

A textbook example of overcoming a market failure for credence goods is the case of U.S. organic markets before and after certification. Prior to specific standards for the production, the market for organics was very small with lenders reluctant to finance operations. Once standards were set and claims were verified, many farmers overcame their reluctance to join the industry, consumers overcame their distrust of product claims, and lenders had a greater understanding of the needs of producers in this new market (Giannakas 2002; Klonsky and Smith 2002; Kostandini, Mykerezi, and Tanellari 2011; Jones, Escalante and Hofner 2015).

A major piece of legislation in support of increasing transparency and standardization in voluntary agriculturalcarbon programs is the Climate Solutions Act of 2021 (GCSA), passed by the U.S. Senate on June 24, 2021. If ratified by the U.S. House of Representatives, the GCSA will assist farmers, ranchers, and private forest landowners to participate in voluntary carbon markets and adopt conservation practices. Particularly, the legislation will provide the U.S. Department of Agriculture (USDA) authority to create a GHG Technical Assistance Provider and a Third-party Verifier Certification Program. Although the bill does not specify any details about carbon markets, it instructs the Secretary of Agriculture to provide necessary definitions of the markets and determine the rules for the certification program (Crespi and Tidgren 2021). An effort to standardize or create equivalencies to the amount of carbon credit generated by the same practice in the same farm across private programs would add transparency and reduce systemic risks for potential participants.

An international survey conducted by the United Nations Development Programme (UNDP) and the University of Oxford found that 64% of respondents agree that climate change is a global emergency and call for broad climate policies, such as more renewable energy, adopting climate-friendly farming practices, and conserving forests and land (UNDP 2021). Likewise, about 65% of surveyed Americans desired the federal government to take more action on climate change (Tyson and Kennedy 2020). However, the implementation of climate policy has encountered multiple challenges, in part due to less than full agreement on the science of climate change. Additionally, the disbelief of a substantial share of representatives in the U.S. Congress about the science of climate change slows environmental policy discussions. Drennen and Hardin (2021) reported that 26% of elected officials in the 117th Congress reject the evidence of human contribution to climate change and support the continued usage fossil fuels.

Alternative Scenarios for Ag Carbon

Considering the functioning of voluntary carbon markets and the challenges described in the previous sections, we propose four possible scenarios for the future of voluntary agricultural carbon credits in the United States, based on the level of corporate demand for and the value of agricultural carbon credits received by farmers.

Scenario 1: High demand for high-value ag carbon credits

If corporate demand for carbon credits is high and sustained, and agricultural carbon credits are traded at high values, then the carbon market will generate a valuable and stable source of revenue for participating farmers. A credible measuring, reporting, and verification (MRV) system for agricultural carbon credits is necessary to achieve this scenario, as well as limited competition from international industrial carbon sinks, forestry, and other sources (either via limited quantities at similar prices, or via a segmented market for carbon credits with different prices).

This scenario assumes large-scale adoption of conservation practices according to production protocols that generate high-quality credits, and puts the agricultural sector at the forefront of global warming mitigation. A sustained demand for agricultural carbon credits and widespread farmer participation would result in liquid markets with moderate price volatility, supported by robust financing and adequate risk-management services for farmers and purchasers of credits. Scenario 1 would be reinforced by the development of complementary value chains for low-carbon commodities that trade at a premium over conventional commodities, as well as by articulated protocols that would allow producers to migrate across carbon programs.

Scenario 2: High demand for low-value ag carbon credits

If corporate demand for carbon credits is high but the perceived quality of agricultural carbon credits is low, then agricultural carbon markets will likely be small and underdeveloped. A necessary condition for Scenario 2 to exist is that competition from other sources of low-value carbon credits be limited. Scenario 2 is likely to occur in the absence of a credible MRV system for agricultural carbon credits, resulting in participants implementing only the least-cost practices to generate carbon credits or practices that would be implemented even in the absence of carbon payments. Market liquidity would be low, with high volatility around low average prices, and limited financing and risk-management services for farmers and purchasers of credits.

Scenario 3: Low demand for high-value ag carbon credits

If corporate demand for carbon credits is low but participation in voluntary carbon programs is highly subsidized (directly through cost-share programs to implement certain practices, or indirectly through crop insurance premium deductions or tax credits), to the extent that market prices for carbon credits become of secondary importance to farmers, then an inefficient market for agricultural carbon would develop, funded by present and future taxpayers. The focus of participating farmers would turn to complying with regulations to receive government payments or subsidies (rent-seeking behavior), and the cost of administering carbon programs would be largely absorbed by the sponsoring government agencies.

A low corporate demand for carbon credits could stem from a weak MRV system or high competition from other sources of carbon credits. Market liquidity would be low, with high volatility around low average prices, and limited private financing and risk-management services for farmers and purchasers of credits. Scenario 3 would be unsustainable in the long run.

Scenario 4: Low demand for low-value ag carbon credits

If corporate demand for carbon credits is low and the perceived quality of agricultural carbon credits is low, resulting in low credit prices and possibly but not necessarily including adverse selection or moral hazard in the marketplace, then agricultural carbon markets will likely collapse. A low corporate demand for carbon credits could stem from a weak MRV system or high competition from other sources of carbon credits. A limited adoption of conservation practices will likely generate high volatility around low average agricultural credit prices, and steer farmers away from carbon markets. There would be limited private financing and risk-management services for farmers and purchasers of credits. Scenario 4 would be unsustainable in the short run.

Conclusion

This article attempts to increase the understanding of voluntary agricultural carbon programs in the United States by describing the linkages between international agreements to prevent further global warming to international, national, and regional carbon pricing mechanisms that in turn provide market signals to consumers and suppliers of carbon credits. By discussing the current state of voluntary agriculture carbon programs in the United States, its current and future challenges, and by providing an assessment of four possible scenarios for the future of agricultural carbon, this article raises awareness among policymakers and agricultural stakeholders about the obstacles that need to be removed in order for agricultural carbon markets to succeed.

References

Acadia Center. 2019. The Regional Greenhouse Gas Initiative: 10 Years in Review. Available at https://acadiacenter.org/resource/the-regional-greenhouse-gas-initiative-ten-years-in-review/. Last accessed 11/02/2021.

Aichele, R., and G. Felbermayr. 2015. Kyoto and Carbon Leakage: An empirical Analysis of the Carbon Content of Bilateral Trade. *The Review of Economics and Statistics* 97(1): 104–115.

Akerlof, G. 1970. The Market for “Lemons”: Quality Uncertainty and the Market Mechanism," *Quarterly Journal of Economics* 84:488-500.

Allen, M., K. Axelsson, B. Caldecott, T. Hale, C. Hepburn, C. Hickey, E. Mitchell-Larson, Y. Malhi, F. Otto, N. Seddon, and S. Smith. 2020. The Oxford Principles for Net Zero Aligned Carbon Offsetting. Smith School of Enterprise and the Environment, University of Oxford, United Kingdom.

Angelopoulou T., N. Tziolas, A. Balafoutis, G. Zalidis, D. Bochtis. 2019. Remote Sensing Techniques for Soil Organic Carbon Estimation: A Review. *Remote Sensing*, 11(6), 676. https://doi.org/10.3390/rs11060676

Asen, E. 2021. Carbon Taxes in Europe. Tax Foundation. Available at https://taxfoundation.org/carbon-taxes-in-europe-2021/. Last accessed 08/15/2021.

Bithas, K. and D. Latinopoulos. 2021. “Managing Tree-Crops for Climate Mitigation. An Economic Evalution Trading-Off Carbon Sequestration with Market Goods.” *Sustainable Production and Consumption* 27: 667-678.

Black, R., K. Cullen, B. Fay, T. Hale, J. Lang, S. Mahmood, S.M. Smith. 2021. Taking Stock: A global assessment of net zero targets. Energy & Climate Intelligence Unit and Oxford Net Zero. Available at https://ca1-eci.edcdn.com/reports/ECIU-Oxford_Taking_Stock.pdf?mtime=20210323005817&focal=none. Last accessed 10/6/2021.

Bonroy, O. and C. Constantatos. 2015. On the Economics of Labels: How Their Introduction Affects the Functioning of Markets and the Welfare of All Participants. *American Journal of Agricultural Economics* 97:239-259.

Buckley, C. 2021. China Opened a National Carbon Market. Here’s Why it Matters. New York Times. Available at https://www.nytimes.com/2021/07/16/business/energy-environment/china-carbon-market.html. Last accessed 08/15/2021.

Burke, M., S. Hsiang, and E. Miguel. 2015 Global Non-linear Effect of Temperature on Economic Production. *Nature* 527: 235–239. https://doi.org/10.1038/nature15725

CARB. 2015. Overview of ARB Emissions Trading Program. California Environmental Protection Agency. Available at https://ww2.arb.ca.gov/sites/default/files/cap-and-trade/guidance/cap_trade_overview.pdf. Last accessed 11/03/2021.

CARB. 2019. Unofficial Electronic Version of the Regulation for the California Cap on Greenhouse Gas Emissions and Market-based Compliance Mechanisms. Available at https://ww2.arb.ca.gov/sites/default/files/2021-02/ct_reg_unofficial.pdf. Last accessed 11/03/2021.

Castagné, M., S. Lickel, T. Ritter, and G. Dufrasne. 2020. Carbon Markets and Agriculture: Why Offsetting is Putting Us on the Wrong Track. Institute for Agriculture and Trade Policy. Available at https://www.iatp.org/sites/default/files/2020-11/Land%20Carbon%20Brief_VF_2020.pdf. Last accessed 08/15/2021.

Caswell, J., and M. Mojduszka. 1996. Using Information Labelling to Influence the Market for Quality in Food Products. *American Journal of Agricultural Economics* 78:1248-1253.

Chambers, R.G., and S. Pieralli. 2020. The sources of measured US agricultural productivity growth: Weather, technological change, and adaptation. *American Journal of Agricultural Economics* 102(4): 1198–1226.

Claassen, R., E.N. Duquette, D.J. Smith. 2018. Additionality in U.S. Agricultural Conservation Programs. *Land Economics* 94(1): 19–35.

Climate Action Tracker. 2020. Paris Agreement Turning Point. Available at https://climateactiontracker.org/documents/829/CAT_2020-12-01_Briefing_GlobalUpdate_Paris5Years_Dec2020.pdf. Last accessed 08/15/2021.

CME Group. 2021a. CME Group Announces First Trades of Global Emissions Offset (GEO) Futures. Available at https://www.cmegroup.com/media-room/press-releases/2021/3/03/cme_group_announcesfirsttradesofglobalemissionsoffsetgeofutures.html. Last accessed 08/16/2021.

CME Group. 2021b. CME Group Announces First Trades of Nature-Based Global Emissions Offset (N-GEO) Futures. Available at https://www.cmegroup.com/media-room/press-releases/2021/8/03/cme_group_announcesfirsttradesofnature-basedglobalemissionsoffse.html. Last accessed 08/16/2021.

Crespi, J.M., and S. Marette. 2003. Some Economic Implications of Public Labelling. Journal of Food Distribution Research 34: 83–94.

Crespi, J.M., and S. Marette. 2005. Ecolabeling Economics: Is Public Involvement Necessary? In Environment, Information and Consumer Behavior, New Horizons in Environmental Economics, ed. Signe Krarup and Clifford S. Russell, 93–109. Northampton: Edward Elgar Publishing.

Crespi, J.M. and K. Tidgren. 2021. The First Legal Step for an Agricultural Carbon Market is in the Growing Climate Solutions Act of 2021. Policy brief 21-PB 33. Center for Agricultural and Rural Development, Iowa State University.

Darby, M., and E. Karni. 1973. Free Competition and the Optimal Amount of Fraud. Journal of Law and Economics 16(1):67-88.

Drennen, A., and S. Hardin. 2021. Climate Deniers in the 117th Congress. Center of American Progress. Available at https://www.americanprogress.org/issues/green/news/2021/03/30/497685/climate-deniers-117th-congress/. Last accessed 08/15/2021.

EEX. 2021. Emission Spot Primary Market Auction Report 2021. Available at https://www.eex.com/en/market-data/environmental-markets/eua-primary-auction-spot-download. Last accessed 11/08/2021.

Environmental Defense Fund. 2020. Analytical Report on the Status of the China GHG Voluntary Emission Reduction Program. Available at https://www.edf.org/sites/default/files/documents/Analytical-Report_on_the_Status_of_the_China_GHG_Voluntary_Emission_Reduction_Program-ENG.pdf. Last accessed 08/28/2021.

EPA. 2021a. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2019. Available at https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2019. Last accessed 08/27/2021.

EPA. 2021b. Greenhouse Gas Inventory Data Explorer. Available at https://cfpub.epa.gov/ghgdata/inventoryexplorer/#agriculture/entiresector/allgas/category/all. Last accessed 08/11/2021.

European Commission. 2021a. Development of EU ETS (2005-2020). Available at https://ec.europa.eu/clima/eu-action/eu-emissions-trading-system-eu-ets/development-eu-ets-2005-2020_en. Last accessed 11/08/2021.

European Commission. 2021b. Effort Sharing 2021-2030: Targets and Flexibilities. Available at https://ec.europa.eu/clima/policies/effort/regulation_en. Last accessed 08/28/2021.

European Commission. 2021c. Questions and Answers - The Effort Sharing Regulation and Land, Forestry and Agriculture Regulation. QANDA/21/3543. Brussels, Belgium. 14 July. Available at https://ec.europa.eu/commission/presscorner/detail/en/qanda_21_3543. Last accessed 10/27/2021.

Friedman, L. 2021. Democrats Plan Carbon Tariff That Hauls in Billions a Year. The New York Times-Late Edition. July 20. Available online at https://www.nytimes.com/2021/07/19/climate/democrats-border-carbon-tax.html. Last accessed on 10/27/2021.

Giannakas, K. 2002. Information Asymmetries and Consumption Decisions in Organic Food Product Markets. *Canadian Journal of Agricultural* Economics 50:35-50.

Gold Standard. 2021. Gold Standard for the Global Goals Fee Schedule. Available at: https://globalgoals.goldstandard.org/fees/. Last accessed 08/20/2021.

Gramig, B. M., and N. J.O. Widmar. 2018. Farmer Preferences for Agricultural Soil Carbon Sequestration Schemes. *Applied Economic Perspectives and Policy*, 40(3), 502-521.

Gramig, B.M., and N. J.O. Widmar. 2018. Farmer Preferences for Agricultural Soil Carbon Sequestration Schemes. *Applied Economic Perspectives and Policy* 40(3): 502–521.

Griesinger, W. 2010. Death to the Chicago Climate Exchange ($7.40 to a nickel per CO2 ton, the market has spoken). MasterResource. Available at: https://www.masterresource.org/chicago-climate-exchange/death-chicago-climate-exchange/. Last accessed 08/15/2021.

Haim, D., E.M. White, and R.J. Alig. 2016. Agriculture Afforestation for Carbon Sequestration Under Carbon Markets in the United States: Leakage Behavior from Regional Allowance Programs. *Applied Economic Perspectives and Policy* 38(1): 132–151.

ICE. 2011. CCX Fact Sheet. Available at https://www.theice.com/publicdocs/ccx/CCX_Fact_Sheet.pdf. Last accessed 08/15/2021.

ICE. 2021. EUA UK Auctions. Available at https://www.theice.com/marketdata/reports/148. Last accessed 11/08/2021.

International Carbon Action Partnership. 2021a. USA-California Cap-and-Trade Program. Available at https://icapcarbonaction.com/en/?option=com_etsmap&task=export&format=pdf&layout=list&systems%5B%5D=45#:~:text=Market Stability Provisions AUCTION RESERVE,by the Consumer Price Index. Last accessed 11/03/2021.

International Carbon Action Partnership. 2021b. EU Emissions Trading System (EU ETS). Available at https://icapcarbonaction.com/en/?option=com_etsmap&task=export&format=pdf&layout=list&systems%5B%5D=43. Last accessed 11/03/2021.

International Carbon Action Partnership. 2021c. China National ETS. Available at https://icapcarbonaction.com/en/?option=com_etsmap&task=export&format=pdf&layout=list&systems%5B%5D=55. Last accessed 08/28/2021.

IPCC. 2021. Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press. In Press.

Jackson-Smith, D., M. Hailing, E. de la Hoz, J. McEvoy, and J. Horsburgh. 2010. Measuring Conservation Program Best Management Practice Implementation and Maintenance at the Watershed Scale. *Journal of Soil and Water Conservation* 65(6):413–423.

Jones, G., C. Escalante, and H. Rusiana. 2015. Reconciling Information Gaps in Organic Farm Borrowers' Dealings with Farm Lenders. *Agricultural Finance Review* 75(4):469–483.

Joppa, L., A. Luers, E. Willmott, S.J. Friedmann, S.P. Hamburg, and R. Broze. 2021. "Microsoft's Million-tonne CO2-removal Purchase – Lessons for Net Zero." *Nature* 597:629–632. Available at https://media.nature.com/original/magazine-assets/d41586-021-02606-3/d41586-021-02606-3.pdf. Last accessed 10/6/2021.

Khanna, M. 2017. Nexus between Food, Energy and Ecosystem Services in the Mississippi River Basin: Policy Implications and Challenges. *Choices Magazine* 32(4):1–9.

Kiesel, K. and S.B. Villas-Boas. 2013. Can Information Costs Affect Consumer Choice? Nutritional Labels in a Supermarket Experiment. International Journal of Industrial Organization 31:153-163.

Klonsky K., M.D. Smith. 2002. Entry and Exit in California's Organic Farming Sector In *Economics of Pesticides, Sustainable Food Production, and Organic Food Markets. Advances in the Economics of Environmental Resources, Vol. 4*, ed. Darwin C. Hall and L. Joe Moffitt, 139-165. Bingley: Emerald Group Publishing Limited. Accessed October 14, 2021

Kostandini, G., E. Mykerezi, and E. Tanellari. 2011. "Viability of Organic Production in Rural Counties: County and State-Level Evidence from the United States." *Journal of Agricultural and Applied Economics* 43(3):443–451.

Marette, S. 2014. Economic Benefits Coming from the Absence of Labels Proliferation. *Journal of Agricultural and Food Industrial Organization*. 12:1-9.

Marette, S. and J. Roosen. Bans and Labels with Controversial Food Technologies. In The Oxford Handbook of the Economics of Food Consumption and Policy. J.L. Lusk, J. Roosen and J.E. Shogren (eds.). Oxford University Press, 2011:499-519.

Murray, B. C. 2015. Why Have Carbon Markets Not Delivered Agricultural Emission Reductions in the United States?. *Choices Magazine* 30(2), 1–5.

National Academies of Sciences, Engineering, and Medicine. 2019. Negative Emissions Technologies and Reliable Sequestration: A Research Agenda. Washington, DC: The National Academies Press. https://doi.org/10.17226/25259

Njuki, E., B.E. Bravo-Ureta, and C.J. O'Donnell. 2018. A New Look at the Decomposition of Agricultural Productivity Growth Incorporating Weather Effects. *PLoS One* 13(2). https://doi.org/10.1371/journal.pone.0192432

Ogle, S. M., A. Swan, and K. Paustian. 2012. No-till Management Impacts on Crop Productivity, Carbon Input and Soil Carbon Sequestration. *Agriculture, Ecosystems and Environment* 149: 37–49.

Ortiz-Bobea, A., E. Kinppenberg, and R. G. Chambers. 2018. Growing Climatic Sensitivity of U.S. Agriculture Linked to Technological Change and Regional Specialization. *Science Advances* 4(12), https://doi.org/10.1126/sciadv.aat4343.

Paris Agreement to the United Nations Framework Convention on Climate Change, Dec. 12, 2015, T.I.A.S. No. 16-1104. Available at https://unfccc.int/sites/default/files/english_paris_agreement.pdf. Last accessed 08/11/2021.

PEW Center on Global Climate Change. 2009. American Clean Energy and Security Act of 2009. Available at https://www.c2es.org/wp-content/uploads/2009/06/Waxman-Markey-short-summary-revised-June26.pdf. Last accessed 08/23/2021.

Plastina, A. 2021. How do Data and Payments Flow through Ag Carbon Programs? Iowa State University Extension and Outreach, *Ag Decision Maker* File A1-77. Available at https://www.extension.iastate.edu/agdm/crops/pdf/a1-77.pdf

Plastina, A. and O. Wongpiyabovorn. 2021. How to Grow and Sell Carbon Credits in US Agriculture. Iowa State University Extension and Outreach, *Ag Decision Maker* File A1-76. Available at https://www.extension.iastate.edu/agdm/crops/pdf/a1-76.pdf

Plastina, A., S.H. Lence, and A. Ortiz-Bobea. 2021. How Weather Affects the Decomposition of Total Factor Productivity in U.S. Agriculture. *Journal of the International Association of Agricultural Economists* 52:215–234.

Raymond, L., and G. Shively. 2008. Market-Based Approaches to CO2 Emissions Reductions. *Choices Magazine* 23(1):38–40.

Ribera, L.A., and B.A. McCarl. 2009. Carbon Markets: A Potential Source of Income for Farmers and Ranchers. AgriLife Extension, Texas A&M University System.

Ribera, L.A., B.A. McCarl, and J. Zenteno. 2009. Carbon Sequestration: A Potential Source of Income for Farmers. *Journal of the American Society of Farm Managers and Rural Appraisers* 70–77.

Roe, B.E. and I. Sheldon. 2007. Credence Good Labelling. The Efficiency and Distributional Implications of Several Policy Approaches. *American Journal of Agricultural Economics* 89:1020-1033.

Roe, B.E., M.F. Teisl and C. R. Deans. 2014. The Economics of Voluntary versus Mandatory Labels. *Annual Review of Resource Economics* 6:1-21.

Sabasi, D., and C.R. Shumway. 2018. Climate change, health care access and regional influence on components of U.S. agricultural productivity. *Applied Economics* 50(57):6149–6164.

Sanderson, B.M., and B.C. O'Neill. 2020. Assessing the Costs of Historical Inaction on Climate Change. *Scientific Reports* 10, 9173, https://doi.org/10.1038/s41598-020-66275-4

Sawadgo, W., and A. Plastina. 2021. “Do Cost-share Programs Increase Cover Crop Use? Empirical Evidence from Iowa.” *Renewable Agriculture and Food Systems* 36(6):527–535. doi:10.1017/S1742170521000132.

Sawadgo, W., and A. Plastina. *Forthcoming*. “The Invisible Elephant: Disadoption of Conservation Practices in the United States.” *Choices Magazine*. Accepted for publication on August 22, 2021.

Secchi, S., and C. Jones. 2021. Opinion: With Iowa's and the Ag Industry's Carbon Efforts, Plenty of Reason to Question Motives. Des Moines Register. Available at https://www.desmoinesregister.com/story/opinion/columnists/iowa-view/2021/07/04/carbon-sequestration-credits-iowa-agriculture-industry-motives/7819629002/. Last accessed 08/15/2021.

Teisl. M.F. and B.E. Roe. 1998. The Economics of Labeling: An Overview of Issues for Health and Environmental Disclosure. *Agricultural and Resource Economics Review* 27:140-150.

Toliver, D. K., J.A. Larson, R.K. Roberts, B.C. English, D.G. De La Torre Ugarte, and T.O. West. 2012. Effects of No-till on Yields as Influenced by Crop and Environmental Factors. *Agronomy Journal* 104(2):530-541.

Toplensky, R. 2021. Europe’s Carbon Prices Are Going Global. *Wall Street Journal*. Available at https://www.wsj.com/articles/europes-carbon-prices-are-going-global-11626269612. Last accessed 08/28/2021.

Tyson, A., and B. Kennedy. 2020. Two-Thirds of Americans Think Government Should Do More on Climate. Pew Research Center. Available at https://www.pewresearch.org/science/2020/06/23/two-thirds-of-americans-think-government-should-do-more-on-climate/. Last accessed 08/15/2021.

UNDP. 2021. World’s Largest Survey of Public Opinion on Climate Change: A Majority of People Call for Wide-ranging Action. Available at https://www.undp.org/press-releases/worlds-largest-survey-public-opinion-climate-change-majority-people-call-wide. Last accessed 08/28/2021.

UNFCCC. 2008. Kyoto Protocol Reference Manual on Accounting of Emissions and Assigned Amount. Climate Change Secretariat. Bonn, Germany. Available at https://unfccc.int/kyoto_protocol. Last accessed 9/29/2021.

UNFCCC. 2011. Fact sheet: Climate change science - the status of climate change science today. Available at https://unfccc.int/files/press/backgrounders/application/pdf/press_factsh_science.pdf. Last accessed 08/20/2021.

UNFCCC. 2013. Annual compilation and accounting report for Annex B Parties under the Kyoto Protocol for 2013. Available at https://unfccc.int/documents/7924. Last accessed 11/08/2021.

UNFCCC. 2015. Annual compilation and accounting report for Annex B Parties under the Kyoto Protocol for 2015. Available at https://unfccc.int/documents/8972. Last accessed 11/08/2021.

UNFCCC. 2016. China First NDC. Available at https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/China%20First/China's%20First%20NDC%20Submission.pdf. Last accessed 08/15/2021.

UNFCCC. 2020. European Union First NDC (Updated submission). Available at https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/European%20Union%20First/EU_NDC_Submission_December%202020.pdf. Last accessed 08/15/2021.

UNFCCC. 2021a. United States of America First NDC (After rejoining the Paris Agreement). Available at https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/United%20States%20of%20America%20First/United%20States%20NDC%20April%2021%202021%20Final.pdf. Last accessed 08/15/2021.

UNFCCC. 2021b. What is the Kyoto Protocol? Available at https://unfccc.int/kyoto_protocol. Last accessed 10/2/2021.

USGCRP. 2018. Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, 1515. https://doi.org/10.7930/NCA4.2018

van Kooten, G. C. 2008. A Perspective on Carbon Sequestration as a Strategy for Mitigating Climate Change. *Choices Magazine* 23(1):24-27.

Wade, T., R. Claassen, and S. Wallander. 2015. Conservation-Practice Adoption Rates Vary Widely by Crop and Region. Economic Information Bulletin Number 147, Economic Research Service, United States Department of Agriculture.

Weiss, D. J. 2010. Anatomy of a Senate Climate Bill Death. Center for American Progress. Available at https://www.americanprogress.org/issues/green/news/2010/10/12/8569/anatomy-of-a-senate-climate-bill-death/. Last accessed 08/23/2021.

West, T. O., and G. Marland. 2002. A Synthesis of Carbon Sequestration, Carbon Emissions, and Net Carbon Flux in Agriculture: Comparing Tillage Practices in the United States. *Agriculture, Ecosystems and Environment*, 91(September), 217-232.

Wongpiyabovorn, O., A. Plastina, and S. Lence. 2021. Futures Market for Ag Carbon Offsets under Mandatory and Voluntary Emission Targets. Agricultural Policy Review, Fall 2021. Center for Agricultural and Rural Development, Iowa State University. Available at www.card.iastate.edu/ag_policy_review/article/?a=127.

World Bank. 2020. State and Trends of Carbon Pricing 2020. World Bank, Washington D.C.

World Bank. 2021. Carbon Pricing Dashboard. Available at https://carbonpricingdashboard.worldbank.org/map_data. Last accessed 10/11/2021.

U.S. Agriculture as a Carbon Sink: From International Agreements to Farm Incentives

Appendix

Oranuch Wongpiyabovorn, Alejandro Plastina, and John Crespi

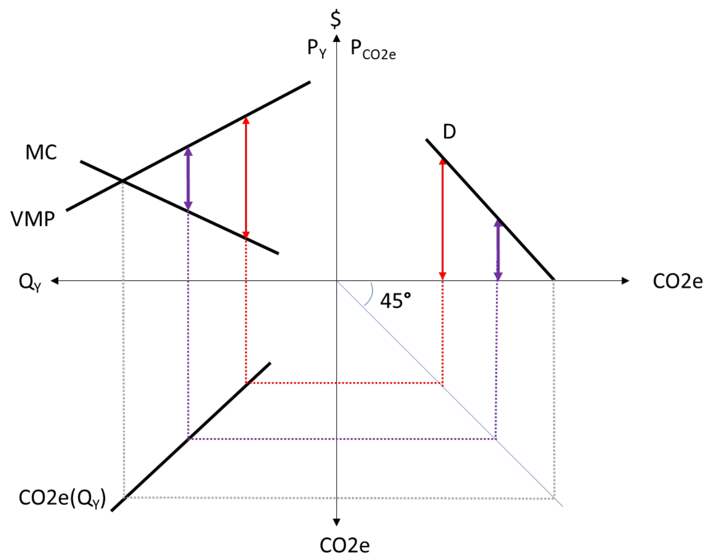


Figure A1. Derivation of the demand curve for CO2e units, D

Note: VMP is value of marginal product for output Q_Y; MC is marginal cost for output Q_Y; and CO2e(Q_Y) indicates the units of CO2e emissions required to produce Q_Y for a fixed technology (i.e., a technical relationship).