A Review of the Role of Agriculture in Mandatory and Voluntary Carbon Pricing Mechanisms

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Dr. Oranuch Wongpiyabovorn conducted background research and co-developed the manuscript; Dr. Alejandro Plastina co-developed the manuscript.

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Abstract

This article provides a systematic review of the role of agriculture as a source of carbon credits for major mandatory and voluntary carbon pricing mechanisms around the world, as well as of large-scale initiatives to limit greenhouse gases (GHG) emissions from the agricultural sector. Among the mandatory carbon pricing mechanisms, the emissions trading systems (ETSs) in the European Union and the United States of America (USA), Australia, and New Zealand are reviewed, along with the EU carbon border adjustment mechanism, Denmark carbon tax on agricultural emissions, and the EU greenhouse gas emission reduction targets for agricultural activities. Among the voluntary carbon pricing mechanisms, current trends in carbon markets in the USA, and the EU are discussed, including efforts to implement high-integrity standards for agricultural carbon credits. Overall, agricultural activities to mitigate climate change are playing a small role in current mandatory carbon pricing mechanisms, while voluntary uses of carbon credits from agricultural activities are competing against credits from other sources and are facing challenges over their integrity concerns.

Running Head: The Role of Agriculture in Carbon Pricing Mechanisms

Keywords: agriculture, carbon credits, carbon farming, carbon pricing, carbon programs, emissions trading system, ETS

Review Methodology

We searched for EU and US mandatory emission trading systems (ETSs) in the World Bank's carbon pricing dashboard and extended the review by visiting each ETS's website. We also conducted online searches on Google using the following keywords: California Cap-and-Trade, Denmark carbon tax, EU ETS, RGGI, Massachusetts Electricity Generator Emissions Limits, New Zealand ETS, Washington Cap-and-Invest, along with the combinations with the following terms: agricultural, emissions, carbon pricing, offsets. For voluntary carbon markets, we searched through the multiple combinations of the following terms: agricultural, Australia, carbon, credits, EU, insets, market, offsets, voluntary, US. In addition, we searched through the Google Scholar database to identify the challenges to high-integrity agricultural carbon credits using the following keywords: agricultural, barriers, carbon, challenges, credits, emissions, market, opportunities, and pricing. Lastly, we used the references from the articles obtained by this method to check for additional relevant materials.

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The Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC) attempts to limit the global average temperature increase to well below 2°C compared to pre-industrial levels, with a preferable goal of 1.5°C, by reducing international greenhouse gas (GHG) emissions. Many countries such as the European Union (EU), Canada, Japan, South Korea, South Africa, and the United Kingdom have proposed reaching net-zero emissions by 2050 (UNFCCC, 2024). The IPCC Sixth Assessment Report also shows that as of October 2021, the climate mitigation plans submitted to the Paris Agreement, called the Nationally Determined Contributions (NDCs), are unlikely sufficient to limit global warming to 1.5°C above pre-industrial levels (IPCC, 2023). Importantly, the global temperature increase will exceed the 2°C goal unless more ambitious mitigation efforts are implemented (IPCC, 2023).

In 2022, global on-farm agricultural emissions—emissions from crop, livestock, on-farm energy use, drained organic soils, and savanna fires—accounted for 14.6% of the total anthropogenic GHG emissions (Food and Agriculture Organization of the United Nations, 2024). More than half of the total agricultural emissions from manure management and enteric fermentation associated with livestock production (55.1%), while emissions from cropping activities (crop residues, burning crop residues, chemical applications, and rice cultivation) contributed to about one-fourth of total agricultural emissions (24.1%).

While emissions from on-farm agricultural production are not regulated for climate purposes in most countries, agricultural activities can be one of the contributors to the Paris Agreement goal. Climate-smart practices can sequester carbon dioxide (CO_2) and reduce GHG emissions from agricultural production, and agricultural soils can act as a carbon sink by storing CO_2 as soil organic carbon. The estimates of global carbon sequestration potential in agricultural

lands considerably vary from 3.3–6.8 billion metric tons of CO_2 (tCO_2) per year (Zomer et al., 2017). This potential is particularly relevant to the discussion on how countries can collectively achieve climate targets when the technology to generate large-scale and permanent removals is too costly for generalized adoption throughout the economy. The current costs of industrial carbon capture and sequestration technologies range approximately between US$50 and US$150 per tCO_2 (Herzog et al., 2024), while the future costs of direct air capture technology were projected to remain expensive, ranging from US$226 to US$835 per tCO_2 at the annual cumulative capacity of 1 billion tCO_2 (Sievert et al., 2024). 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.

Soil carbon enhancement and GHG emissions reduction via agricultural conservation techniques may be more affordable compared to advanced industrial carbon capture and direct air capture technologies. According to Jones and O'Hara (2023), to achieve a reduction of 10 million tCO_2-equivalent (tCO_2e)[1] in the United States of America (USA), using conservation tillage would require about US$30–US$35/tCO_2e, while cover crops would need US$35–US$85/tCO_2e. The reduced fertilizer application by using Enhanced Efficiency Fertilizers (EEFs), e.g., coated-fertilizer, nitrification inhibitor, and urease inhibitor, would not require any carbon payments when increased yield from the application is assumed, otherwise EEF adoption would require over US$100/$tCO_2e$ to reach the total of 10 million tCO_2e reduction.

Apart from cropping emissions reduction potentials, livestock emissions can be mitigated by several approaches, such as improved feed digestibility (a maximum mitigation potential of 0.68 billion tCO_2e/year), manure management (0.01–0.075 billion tCO_2e/year), improved animal productivity and health (0.2 billion tCO_2e/year) (Herrero et al., 2016). In addition, anaerobic digestion facilities can capture livestock methane and utilize it for energy generation or other

applications. The marginal abatement costs vary substantially for livestock emissions, even within the same practices. The required carbon payment for using feed additives to reduce the first 1 million tCO_2e in the USA can range from none to over US\$250/tCO_2e (Jones and O'Hara, 2023). Similarly, adopting digesters and solid separators on dairy and swine farms would require none, about US\$20/tCO_2e, or extremely high carbon prices (Jones and O'Hara, 2023).

Previous literature has identified the agricultural activities that can potential reduce and remove emissions (Chute et al., 2022), influencing factors, barriers to adoption, potential GHG impacts, and cost-effectiveness of alternative pricing mechanisms (OECD, 2022). However, the authors are not aware of any systematic discussion on the role of agricultural practices across the diverse institutional frameworks developed around the globe to price GHG emissions. This article provides a systematic review of the role of agriculture as a source of carbon credits for major mandatory and voluntary carbon markets around the world, as well as of large-scale initiatives to limit GHG emissions from the agricultural sector through alternative carbon pricing mechanisms. Among the mandatory carbon pricing mechanisms, the emissions trading systems (ETSs) in the EU, the USA, Australia, and New Zealand are reviewed, along with the EU carbon border adjustment mechanism, the Denmark carbon tax on agricultural emissions, and the EU greenhouse gas emission reduction targets for agricultural activities. Among the voluntary carbon pricing mechanisms, current trends in carbon markets in the USA and the EU are discussed, including efforts to implement high-integrity standards for voluntary carbon credits. Since this review focuses on carbon pricing instruments, policies and efforts that do not directly target GHG reductions as the main drivers of economic incentives—such as the EU Common Agricultural Policy and U.S. conservation programs[2]—are not included in the review. The rest of the article is organized into a section on mandatory carbon pricing mechanisms, a section on voluntary carbon pricing mechanisms, and a concluding section.

Mandatory Carbon Pricing Mechanisms

One of the most extensively used mandatory carbon pricing mechanisms is the emissions trading system (ETS), also called a cap-and-trade program. In an ETS, a regulator sets an upper limit or a cap on the GHG emissions level from regulated entities. A regulated entity must obtain and surrender emission "allowances" (1 allowance = 1 tCO_2e) equaling to their emissions during the period to avoid penalties. Allowances can be allocated at no cost and distributed through auctions by the regulator, while excess allowances can be traded. Depending on the regulations of each ETS, offsets generated by unregulated sectors may be used in place of allowances. The World Bank (2025) reports 36 ETSs implemented at the national and subnational levels. This section discusses EU ETS and major ETSs in USA, the role of agricultural offsets in those ETSs, and the past and current efforts to mandate agricultural emissions.

EU ETS and ETS2

EU ETS is a mandatory cap-and-trade system for 30 countries—all EU member states and Iceland, Liechtenstein, and Norway—covering about 40% of the EU annual GHG emissions. The EU ETS currently covers GHGs from power generation, energy-intensive industry, commercial aviation, and maritime sectors, but not agriculture (European Commission, 2025). In addition, the EU ETS officially linked with Switzerland ETS on January 1, 2022, offering the flexibilities of using allowances from both ETSs (European Council, 2019).

Phase I (2005–2007) of the EU ETS was characterized by excess of freely allocated EU allowances (EUAs), leading to volatile and low EUA prices (Raymond and Shively, 2008). Phase II (2008–2012) continued with a high proportion of freely allocated EUAs, while EUA auctions started in 2012 (European Commission, 2024a). Nevertheless, the EUA prices remained

low because of lower-than-expected emissions from the global financial crisis. In phase III (2013–2020), the annual target reduction of the emissions cap accelerated. However, EUA auction prices were persistently low in the first half decade, as shown in Figure 1. The potential reason for weak allowance prices was the oversupply of allowances stemming from the economic recession, a high influx of international offset credits, and banked allowances from the previous phase (Hu et al., 2015). Towards the end of the phase, the EUA auction prices greatly increased partially due to the establishment of the Market Stability Reserve in 2018, that resolved the oversupply issue (Dimitrova, 2024). The EU ETS is currently in phase IV (2021–2030). The new legislation "fit for 55" was adopted in 2023 with a more ambitious goal to reduce emissions by at least 55% compared to 1990 levels, tighter caps, and lower free EUA allocations (European Commission, 2025). In addition, fuel suppliers for fuel combustion from buildings, road transportation, and additional small sectors will be legally regulated under a new EU ETS (called EU ETS2). The ETS2 begun emissions monitoring and reporting in 2025 and will become fully operational in 2027 (European Commission, 2023b).

Regional Greenhouse Gas Initiative (RGGI)

The first mandatory ETS in the USA is the RGGI established in 2005 as a cooperative effort among the states of Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, and Vermont. The compliance obligation started in 2009 with the declining cap for CO_2 emissions from fossil fuel power plants with an output exceeding 25 megawatts.

CO_2 allowances are distributed quarterly by RGGI via regional auctions. However, allowance prices have been low throughout the program because actual emissions have typically been lower than the cap. Accordingly, the RGGI allowances were sold at the reserve price (a

price floor) in 10 out of 12 auctions over 2010–2012 and the allowance prices were below US$4.85/$tCO_2$ until 2014 (RGGI, 2025a). The average allowance price jumped to US$22.06/$tCO_2$ in the December 2024 auction, likely owing to stricter caps after the program review in 2017. As a result of the regulations, total CO_2 emissions from power plants in ten RGGI states declined by 44% in 2022, compared to their 2008 level (RGGI, 2025b).

While the RGGI does not directly regulate agricultural emissions, power plants can purchase offsets from agricultural manure methane management, along with landfill methane capture, to be used against their excess CO_2 emissions and in lieu of RGGI allowances. The eligible offsets must be generated from projects within the RGGI states. Only one offset project in the history of RGGI has been listed as an authorized source of offsets, which produced 44,127 tCO_2e through landfill methane capture and destruction in Maryland (RGGI, 2025b). Throughout the life of the initiative, CO_2 offsets were not widely used, representing less than 0.1 million allowances, compared to more than 1 billion allowances sold in auctions. The low usage could be partially attributed to low allowance prices (La Hoz Theuer et al., 2023).

California Cap-and-Trade Program

The California Cap-and-Trade Program, launched in 2013, requires GHG emissions reduction compliance from electricity generators, industrial facilities that emit more than 25,000 tCO_2e annually, distributors of transportation fuel, natural gas and other fuels in the state. These sectors account for about 80% of the state's GHG emissions (CARB, 2025a). The California Air Resource Board (CARB) has set declining emission caps, with emissions targets of at least 40% reduction by 2030, 85% reduction by 2045, compared to 1990 levels, and carbon neutrality by 2045 (CARB, 2025a). California's program was linked with Québec's cap-and-trade program in

2014. The linkage allows the use of allowances issued in Québec's program to meet compliance obligations in California and vice versa.

California's allowances are distributed by CARB via direct allocation and auction. The total direct allocation accounted for about 51% of the total emission cap in 2025 (CARB, 2019, 2024a). Most direct allocations are for power plants (53%) and natural gas suppliers (24%). The rest of the allowances are auctioned off. Figure 2 shows that auction allowance prices have gradually increased from the first auction in 2012 until around 2020 (CARB, 2025b). From 2021, the allowance prices significantly increased, resulting from stricter regulations and post-pandemic economic recovery.

A regulated facility could use offsets from unregulated sectors within the USA to meet up to a small portion of a facility's compliance obligation (CARB, 2025c). The program allows six types of offsets: (i) livestock manure capture, (ii) mine methane capture, (iii) destruction of ozone depleting substances, (iv) rice cultivation, (v) U.S. Forest, and (vi) urban forest. The majority of offsets issued in this program (80.1% of the total offsets) were generated from forestry projects via reforestation, improved forest management, and avoided conversion; while livestock manure capture and rice cultivation accounted for 3.6% and none of total offsets, respectively. The use of offsets accounted for 4.2% of the total emissions in the state during the first three compliance periods (2013–2020) (CARB, 2024b, 2025c). Overall, California's total GHG emissions decreased by 22.1% from 476.3 million tCO_2e in 2012 to 371.1 million tCO_2e in 2022 (CARB, 2024b).

Other Mandatory Carbon Pricing Mechanisms in the USA

Two other states, namely Massachusetts and Washington, also have their own ETSs. While the state of Massachusetts is part of the RGGI, it additionally begun to regulate its large electricity-

generating facilities, that are also regulated by RGGI, through regulation 310 CMR 7.74 in 2018 (Massachusetts Department of Environmental Protection (MassDEP), 2024a). The regulation sets an increasing minimum proportion of electricity sales from clean energy sources requirement and a declining limit for CO_2 emissions. The regulated facilities would need to comply with both RGGI and the state's obligations. All allowances have been distributed by MassDEP through auctions since 2021. However, the allowance clearing prices in this ETS were generally lower than allowance prices in the RGGI, ranging between US$1.25 and US$2.25 in 2024 (MassDEP, 2024b). Offsets generated from unregulated sectors are not allowed in this ETS.

The Washington Cap-and-Invest Program (WCIP) became operational in January 2023 (Washington State Department of Ecology, 2025). The program covers businesses that emit more than 25,000 tCO_2e per year, such as fuel suppliers, natural gas, and electric utilities. In addition, waste-to-energy facilities and railroads will be included starting in 2027 and 2031, respectively. The targets are limiting GHG emissions to 45% below the 1990 levels by 2030, and net-zero emissions by 2050 (Washington State Department of Ecology, 2025). Free allowances are allocated by Washington State Department of Ecology to some entities, especially electricity and natural gas utilities. Furthermore, allowances are quarterly auctioned and can be traded on a secondary market. The first auction was held in February 2023, with the current auction (allowances for the current year) settlement price of US$48.50 per allowance. The current auction settlement prices dropped to a range of US$25.76–US$40.26 in the 2024 auctions (Washington State Department of Ecology, 2025).

The WCIP allows the use of offsets to cover up to 5% of the emissions during the first compliance period (2023–2026), but the coverage limits would be reduced afterward (Washington State Department of Ecology, 2025). Four offset protocols developed by CARB

were adopted by WCIP: forestry, urban forestry, livestock methane capturing projects, and ozone depleting substances. Eligible offsets do not need to be generated from projects within Washington, but they must have direct environmental benefits to the state. Only offsets from three projects of ozone depleting substances have been issued so far (Washington State Department of Ecology, 2024).

The Use of Agricultural Offsets in ETSs

The use of offsets can reduce compliance costs in an ETS (Wang and Wang, 2015), as the costs of emission reductions or emission removals may be lower in nonregulated sectors. The eligible offsets for each ETS considerably differ in terms of geographical and sectoral scope, the share of offsets allowed, and offset protocols (La Hoz Theuer, 2023).

Offset usually play a minor role in meeting compliance targets within the ETSs. Some ETSs, including the EU, New Zealand, United Kingdom, and Massachusetts ETSs do not currently allow for the use of offsets. The EU and New Zealand ETSs allowed the use of international carbon offsets generated under the Kyoto Protocol from 2005–2020 and 2008–mid-2015, respectively. However, these ETSs disallowed the use of any offsets starting in 2021 and 2015 due to disruption in allowance prices, delayed domestic abatement activities, and low-quality concerns (La Hoz Theuer, 2023; Abnett, 2024).

Even when offsets can be used to comply with the emission targets of some ETSs, offsets generated from agricultural sources may not be allowed. This is the case for China, Tokyo, and Saitama ETSs. One of the few agricultural offset projects allowed in some ETSs (RGGI, California, Quebec, and Washington) is livestock manure methane capture. However, except for the California Cap-and-Trade Program, no offset from livestock methane capture has yet been issued. As of January 14, 2025, only 3.6% of the 268.4 million tCO_2e offsets came from

livestock projects. (CARB, 2025c). Total agricultural offsets accounted for 0.2% of the total state emissions in 2013–2020 (CARB, 2024b, 2025c). In addition, Québec ETS is developing a new regulation for offset projects from agricultural fertilizer application improvement (Québec Ministry of Environment, 2023).

Similarly, the Australian ETS, called the Safeguard Mechanism, allows the use of carbon credits from the Australian Carbon Credit Unit (ACCU) Scheme, a voluntary carbon credit system established in 2011. Participants in the ACCU Scheme can generate and sell carbon credits or ACCUs from projects in agriculture, carbon capture and storage, energy efficiency, landfill and waste, mining, oil, and gas, transport, and vegetation (Australia Department of Climate Change, Energy, the Environment and Water (DCCEEW), 2024). The currently eligible agricultural activities are increased soil organic carbon sequestration in pastureland or cropland and improved fertilizer efficiency on irrigated cotton. Beef cattle herd management was permanently suspended from accepting new projects in December 2024 as the method no longer complies with the Offset Integrity Standards (Australia DCCEEW, 2025a). As of 2024, a total of 2.57 million agricultural credits were issued throughout the life of the Scheme, which accounted for 1.6% of the total credits issued from all projects (Australia DCCEEW, 2025b). Over 2019–2024, 2.2 million ACCUs were used to comply with Safeguard Mechanism obligations, while 4.6 million were used to meet voluntary climate targets. However, the majority of ACCUs (60%) were held by entities regulated by the Safeguard Mechanism or related entities in 2024 (Clean Energy Regulator, 2025).

Agricultural offsets provide environmental and economic co-benefits. For example, manure methane capturing can improve air and water quality and be used to produce energy (Aillery et al., 2005; Tauseef et al., 2013). Soil carbon sequestering practices also have the potential co-benefits, such as improved soil health, reduced soil erosion, and enhanced water

holding capacity (Ramseur, 2008; Buck and Palumbo-Compton, 2022). However, this kind of offsets are often criticized in terms of their integrity.

The major concerns over the quality of agricultural offsets include additionality, leakage, permanence, double counting, high transaction costs, and delayed technological development (Ramseur, 2008; van Kooten and Zanello, 2023; Wongpiyabovorn et al., 2023). Broekhoff et al. (2019) classified soil carbon sequestering practices and methane emissions reduction from rice cultivation as higher risk project types based on their quality risks (i.e., additionality, overestimating, leakage, double counting, and permanence), while livestock manure management was categorized as a medium risk project type. In comparison, destruction of ozone depleting substances and landfill methane destruction were seen as lower risk project types.

Other reasons for low usage of agricultural offsets stem from the complexity in implementing offsetting agricultural projects and their relatively high cost per issued offset under mandatory protocols. For instance, methane capture from rice cultivation is accepted since mid-2015 to generate offsets in California Cap-and-Trade Program, but no offsets have ever been issued by this kind of project. The major issues are uncertain emissions estimation and potential increases in emissions from crop switching (Haya et al., 2020).

Mandatory Pricing Schemes for Agricultural Emissions

Beyond traditional ETSs, proposed mandatory programs to reduce GHG emissions from agriculture include agriculture-specific ETSs, carbon taxes, and carbon tariffs. In this subsection, major efforts to implement each of these mandatory programs in the agricultural sector are reviewed.

Pricing GHG emissions from agricultural activities is challenging due to the difficulty in measuring emissions, high measurement costs, high number of entities, the potential impact on

299 food prices, and emissions leakage (Leach, 2022; European Environmental Bureau, 2024).
300 Despite these challenges, ongoing discussion ensued on the role of agricultural emissions in
301 ETSs in New Zealand and the EU. To this date, however, no carbon pricing mechanism in the
302 world mandates caps for agricultural emissions.

303 The New Zealand ETS was announced to include agricultural activities with surrender
304 obligations for fertilizer and animal processors starting in 2025 (Hall, 2024). However, the
305 government passed an amendment bill, which came into force on November 26, 2024, to remove
306 agricultural obligations from its ETS (Jones and Langford, 2024). The major stated reasons for
307 the removal include (i) processor-level pricing unlikely to incentivize on-farm behavioral
308 changes and inability to distinguish on-farm emissions efficiency, (ii) using a single price for all
309 gases contradicting the split gas targets, (iii) potential disruption on price and allocation of
310 emission units for emissions-intensive trade-exposed industries, (iv) sizable administrative,
311 compliance, and data management challenges (Hall, 2024). An alternative pricing system for
312 agricultural emissions is expected to be introduced by 2030 (Jones and Langford, 2024), while a
313 proposed system was as a farm-level split-gas levy for biogenic methane and nitrous oxide
314 emissions from livestock and fertilizer (New Zealand Ministry for the Environment, 2022).

315 Regarding EU countries, the majority of agricultural GHG emissions are currently
316 addressed by two separate regulatory regimes: Effort Sharing Regulation (ESR) and Land Use,
317 Land Use Change, and Forestry (LULUCF) Regulation. The ESR, initially adopted in 2018 and
318 amended in 2023, sets GHG emission reduction targets for agricultural activities and other
319 sectors that fall outside the scope of the EU ETS, which account for 60% of total EU GHG
320 emissions (European Commission, 2023a). Member states' target emission reductions range
321 from 10% to 50% by 2030, in relation to 2005 levels, based on GDP per capita and cost-
322 effectiveness (European Commission, 2023a). The amended LULUCF Regulation from 2023

established the EU net removal target of 310 million tCO_2e from the LULUCF sector by 2030 (Niinisto and Lins, 2024). In addition, the no-debit rule (emissions should not exceed removals) remains in effect until 2025, while the positive net removals rule (removals must be greater than emissions) within the sector will start in 2026. Member states are allowed to trade excess removals among themselves.

The connection between ESR and LULUCF Regulation is the flexibility mechanisms that allow the use of annual emission allocations under the ESR to achieve LULUCF obligations and vice versa (Fridahl et al., 2023). However, the use of LULUCF credits for complying with the ESR is limited to up to 262 million tCO_2e from offsets generated in the land use sector, including agriculture, from 2021 to 2030 (European Commission, 2023a).

The European Commission is considering different policy options to limit GHG emissions from EU on-farm agricultural activities, favoring a separate ETS—AgETS (European Commission: Directorate-General for Climate Action, 2023). Five designs for ETSs were proposed by the European Commission: Directorate-General for Climate Action (2023), including all GHGs, livestock, peatland, upstream, and downstream. However, the policy debate is ongoing with no certain timeline or definition. The potential AgETS is likely to be coherent with the current EU ETS, ERS, and LULUCF Regulation.

The EU also implemented another carbon pricing system in 2023, the Carbon Border Adjustment Mechanism, which aims to prevent carbon leakage by setting a tariff on carbon-intensive goods imported into the EU. The regulated goods include fertilizers, along with other products, such as iron and steel, aluminum, and electricity (European Commission, 2023c). The mechanism is under the transitional period (2023–2025), which currently only involves reporting, but the carbon tariff will be fully in effect in 2026 (European Commission, 2023c). The EU agricultural producers may be affected by this policy through higher fertilizer costs.

Denmark is the first country to announce a plan, in June 2024, to implement a carbon tax on agricultural emissions, which will take effect in 2030, directly imposing a price on agricultural emissions. The regulated agricultural emissions include livestock (cow, pig, and sheep) methane from enteric fermentation and manure and nitrous oxide from nitrogen fertilizer, (Searchinger and Waite, 2024). The effective tax rate will be 120 Danish kroner (US$17) per tCO_2e from 2030–2034 and increase to 300 kroner (US$42) in 2035, with a 60% tax deduction (Brunton, 2024).[3] Additionally, a tax of CO_2 from farming peatlands will be introduced in 2028 at the rate of 40 kroner (US$6) per tCO_2e to encourage peatland restoration (Brunton, 2024).

The inclusion of agricultural emissions in mandatory carbon pricing mechanisms has been widely discussed. Proposed carbon pricing systems for agricultural emissions placed an emphasis on livestock and fertilizer emissions, although none of them are currently in effect. The efforts to limit agricultural emissions through ETSs often face strong opposition from farmers (as observed in New Zealand and the EU), citing the risks of increasing food prices and food security. It should be also noted that price uncertainty under a ETS can increase farmers' production cost volatility, unlike carbon tax (Acworth et al., 2017). The implementation of mandatory carbon pricing in agricultural emissions is still uncertain, with the earliest possible instrument is Denmark's carbon tax beginning in 2030. With a half decade before the implementation and gradual increase in tax rate, livestock producers will have time to adjust their farm management strategies and invest in new technologies to reduce GHG emissions. In addition, financial and technical support for these adjustments might be necessary, especially for small and mid-size farms, which tend to have access to fewer resources.

Voluntary Carbon Pricing Mechanisms

Voluntary carbon markets (VCMs) are the marketplace for carbon credits that are sold to entities to meet voluntary climate targets. The demand for voluntary carbon credits stems mostly from GHG emissions reduction pledges by private companies. Almost 1,500 companies in the USA, 8,200 companies in Europe, and 4,750 companies in other countries around the world have announced voluntary emissions reduction commitments (UNFCCC, 2025).

Carbon credits can be generated from many sources, through emissions removal or emissions reduction in renewable energy, forestry, industrial manufacturing, waste disposal, transportation, household, and agricultural activities. Activities that remove GHG from the atmosphere and store it in a carbon sink, such as afforestation, reforestation, and carbon sequestration are classified as emissions removals, while activities that reduce GHG emissions from project activities, such as improved energy efficiency and GHG capture and destruction from the manufacturing process, are classified as emissions reductions (Forest Trends' Ecosystem Marketplace, 2024). It should be noted that some nature-based projects can generate both emissions removals and reductions credits.

Entities pursuing voluntary climate targets can use carbon offsets and insets to reduce their GHG footprint. Carbon offsetting involves the purchase of verified carbon credits generated from activities elsewhere and using them to compensate for all three scopes of emissions: scope 1—the direct GHG emissions from the entity, scope 2—emissions from electricity generation used by the entity, and scope 3—the indirect GHG emissions from the production of materials used by the entity (Hannay, 2023). Meanwhile, there is no consensus on the definition of carbon insets. Carbon insetting focuses on the scope 3 emissions as it is commonly referred to emissions reduction activities within or around a company' value chain—e.g., suppliers, distributors, retailers, consumers, and end-of-life treatment of sold products (World Business Council for

393 Sustainable Development, 2022; Zaman et al., 2024). Unlike carbon offsets, emissions
394 reductions or removals for insetting may or may not require to be certified by carbon crediting
395 programs (World Business Council for Sustainable Development, 2022). Another crucial
396 difference between carbon offsets and insets is that the former can be used only once by one
397 entity, while the latter can be claimed by multiple entities along the value chain (Zaman et al.,
398 2024).

399 Since VCMs cannot be currently used to comply with emission targets in mandatory
400 carbon pricing systems, their prices tend to be lower than the prices for offsets in mandatory
401 markets, such as the ETSs described in the previous section. According to the 2024 State of the
402 Voluntary Carbon Market Report (Forest Trends' Ecosystem Marketplace, 2024), a total of 111
403 million of carbon credits (1 credit = 1 tCO_2e) were globally traded in VCMs at the average price
404 of US\$6.53/tCO_2e in 2023. Both average price and volume decreased 56% and 11% from record
405 highs in 2022. The declines were partially caused by the criticism over the quality of nature-
406 based carbon credits (from forestry and agriculture). The number of credits issued from all
407 sources declined from 0.5 billion to 0.3 billion in 2023, while the number of credits retired each
408 year remained stable under 0.2 billion (Forest Trends' Ecosystem Marketplace, 2024). Hence,
409 the surplus supply remained at 3.2 billion credits in 2023.

410 Agricultural carbon credits compete for demand against credits from other sectors. The
411 volume of agricultural carbon credits accounted for 4.2% of the total credits globally traded in
412 2023, while the majority of the credits traded (32.7%) were generated from forestry and land use
413 activities (Forest Trends' Ecosystem Marketplace, 2024). Meanwhile, the average agricultural
414 carbon credits price in the global VCMs was US\$6.51 per tCO_2e, US\$3.21 lower than credits
415 from forestry and US\$2.86 higher than credits from energy efficiency and fuel switching (Forest
416 Trends' Ecosystem Marketplace, 2024).

Current Status of VCMs for Agricultural Activities

In recent years, VCMs for agricultural carbon credits are emerging in the USA as a growing number of voluntary private carbon initiatives have begun to offer farmers a long menu of options to generate carbon credits from agricultural practices. A survey of voluntary private carbon initiatives 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 are the most commonly accepted farming practices to generate agricultural carbon credits (Plastina et al., 2024). Carbon initiatives are currently using different standards, registries, carbon estimation models, and verification strategies to issue carbon credits, and these methods are expected to change multiple times before settling for more stable rules. They commonly rely on standards developed by well-known registries, such as Verra's Verified Carbon Standard and Climate Action Reserve, while exact information on the credit issuing process is undisclosed by most initiatives (Plastina et al., 2024). The current supply of agricultural carbon credits in the USA is very limited, but the recent proliferation of voluntary private carbon initiatives could rapidly change that under the right conditions or remain subdued and wither away under unfavorable conditions as it occurred in the 2000s with Chicago Climate Exchange (Wongpiyabovorn et al., 2023). Current market prices for agricultural carbon credits in the USA range between US$30 and US$45 per tCO_2e,[4] despite being strongly supported by venture capital to attract farmers into voluntary carbon programs (Plastina, 2021). Low price of agricultural carbon credit is a major challenge to incentivize new adoption of agricultural carbon crediting projects (Buck and Palumbo-Compton, 2022; Barbato and Strong, 2023).

Similar to the USA, VCMs in the EU (and most other countries) are decentralized. Carbon projects are registered to and generate carbon credits through a variety of registries (e.g., Verra, Climate Action Reserve, American Carbon Registry, and Gold Standard). As mentioned earlier, the standards and protocols vary across registries and are frequently updated. Buyers can purchase carbon credits directly from project developers or via intermediary brokers or retail providers (Spilker and Nugent, 2022). An example for a centralized voluntary carbon market is the Australian Carbon Credit Scheme, where the carbon credits generated through the scheme can be traded and used to meet the voluntary climate goals as discussed in the Use of Agricultural Offsets in ETSs subsection. Nevertheless, carbon credits generated from agricultural activities only accounted for a small portion of the total ACCUs issued.

Apart from the competition with other types of carbon credits, farmers and researchers have expressed concerns over greenwashing from agricultural emissions reductions or removals (Barbato and Strong, 2023; Kelloway, 2023). While corporations use carbon offsets and insets to meet their voluntary climate goals, the integrity of agricultural carbon credits remains controversial challenged by lack of additionality, permanence, and robust quantification methods, as well as by double counting.

Efforts to Improve Integrity of Agricultral Carbon Credits

At the global level, the Integrity Council for the Voluntary Carbon Market (ICVCM), an independent governance body, was established at the 2021 United Nations Climate Change Conference (COP26) to set and maintain high standards of voluntary carbon market. In 2023, the ICVCM published Core Carbon Principles (CCPs), which set a global benchmark for high-integrity voluntary carbon projects in terms of three major aspects: governance, emissions impact, and sustainable development (ICVCM, 2024). In addition, the ICVCM assesses carbon

crediting programs and their categories of carbon credits (protocols and methodologies) to determine if they align with CCPs (ICVCM, 2024). While CCPs provide guidance on the supply side, another organization, the Voluntary Carbon Markets Integrity (VCMI), developed a Claims Code of Practice, addressing the integrity on the demand side. The Claims Code of Practice outlines procedure for companies to credibly use voluntary carbon credits to achieve their climate commitments (VCMI, 2024).

A major piece of legislation in support of increasing transparency and standardization in voluntary U.S. agricultural carbon credits is the Growing Climate Solutions Act, as a part of the Consolidation Appropriations Act of 2023, which has become law on December 29, 2022. The legislation has provided the U.S. Department of Agriculture authority to create a GHG Technical Assistance Provider and a Third-party Verifier Certification Program, whose establishing intent was announced in February 2024. This program would help farmers, ranchers, and private forest landowners to participate in VCMs and adopt conservation practices. Although the bill does not specify any details about VCMs, it instructs the Secretary of Agriculture to provide necessary definitions of the markets and determined the rules for the certification program (Crespi and Tidgren, 2021). In May 2024, the Biden administration released principles for participants in U.S. VCMs—both buyers and sellers—to ensure high integrity in claimed voluntary credits (U.S. Department of the Treasury, 2024). However, the future of the Certification Program is uncertain due to the reshuffling of climate priorities under the Trump administration.

Meanwhile, the EU adopted the Carbon Removals and Carbon Farming Certification (CRCF) Regulation in April 2024, which created a certification framework for voluntary carbon credits generated from carbon removals, carbon farming, and carbon storage (European Commission, 2024b). These credits will be verified by a third-party and certified by an EU-wide

registry once it is established by 2028. The carbon credits generated from these projects will be traded in VCMs, but their potential to be used in the EU ETS is uncertain.

Finally, during the 2024 United Nations Climate Conference (COP29), Parties to the Paris Agreement agreed on methodological guidelines and standards for credit measurement and rules to improve transparency and accountability (Mahul and Azizova, 2024), which make Article 6 of the Paris Agreement fully operational after its adoption in 2015. Article 6 offers international climate collaboration through high integrity carbon markets and non-market mechanisms, which could provide more affordable solutions for countries to meet their climate goals. It would enable international trade of carbon credits through a centralized carbon market (UNFCCC, 2023).

The implementation of the policies, standards and guidance frameworks discussed in the present subsection would enhance confidence in VCMs and lead to demand increases. However, the impact of these standards is yet to be observed. In the absence of strong price signals to farmers and ranchers and growing demand for agricultural carbon credits from entities with climate targets, the most likely scenario is one where the market for agricultural carbon remains subdued and only the "low hanging fruit" practices are implemented (Wongpiyabovorn et al., 2023).

Conclusions

This article reviews the role of agriculture as a source of emissions reduction and removals across mandatory and voluntary carbon pricing schemes. Despite the attractive prices paid for carbon offsets in compliance markets such as the California Cap-and-Trade Program and the EU ETS, the supply of agricultural offsets for those markets has been virtually inexistent, due mainly to the very limited set of agricultural practices allowed to generate offsets by the ETSs'

511 regulations. VCMs present a unique opportunity to the agricultural sector to become more
512 sustainable and contribute to climate targets due to the enormous upward potential to scale-up
513 emissions removals and reductions with existing technologies under appropriate institutional
514 frameworks as more robust protocols are developed to generate credible and valuable carbon
515 offsets and insets. However, competition with credits from forestry and other sources, relatively
516 low prices, and concerns about the integrity of agricultural credits currently pose major unsolved
517 challenges that limit the extent of voluntary markets for agricultural carbon credits.

[1] Generally, GHGs are measured in terms of CO_2e for comparison on the basis of their global warming potential (i.e., how much energy the emissions of 1 metric ton of a gas will absorb over a given period of time, relative to the emissions of 1 tCO_2). The global warming potentials of methane and nitrous oxide are 27–30 and 273, respectively, over a 100-year period, compared to a global warming potential of 1 for CO2 (Forster et al., 2021).

[2] U.S. Department of Agriculture administers several voluntary conservations programs, including the Conservation Reserve Program (CRP), the Environmental Quality Incentives Program (EQIP), the Conservation Stewardship Program (CSP), and Conservation Technical Assistance (CTA), which provides financial and technical support on conservation practices, including those that have the potential to mitigate climate change. However, the economic incentives provided by those conservation programs are not directly linked to and neither directly target carbon credits.

[3] 1 Danish krone = 0.14 USD.

[4] This price information is obtained from publicly available data from each initiative's website, although some initiatives do not disclose this information. In addition, carbon prices for some initiatives, such as Carbon by Indigo, vary based on the market. Carbon by Indigo

(https://app.indigoag.com/programs/how-much-can-i-earn-carbon-farming) estimates carbon price of US$45/t$CO_2$e. Nutrien's Sustainable Nitrogen Outcomes Program (https://info.nutrienagsolutions.com/sno) and Cargill's RegenConnect (https://www.cargillag.com/grow-sustainably/regenconnect) offers US$35/t$CO_2$e. Truterra Carbon Program (https://admin.truterraag.com/Truterraag/media/TTDocuments/25-1-TT-carbon-Tech-sheet_VFL112624.pdf) provides an incentive of US$30/t$CO_2$e.

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Figure 1. EU ETS Auction Spot Prices from 2013 to 2024.

Source: European Energy Exchange (2025)

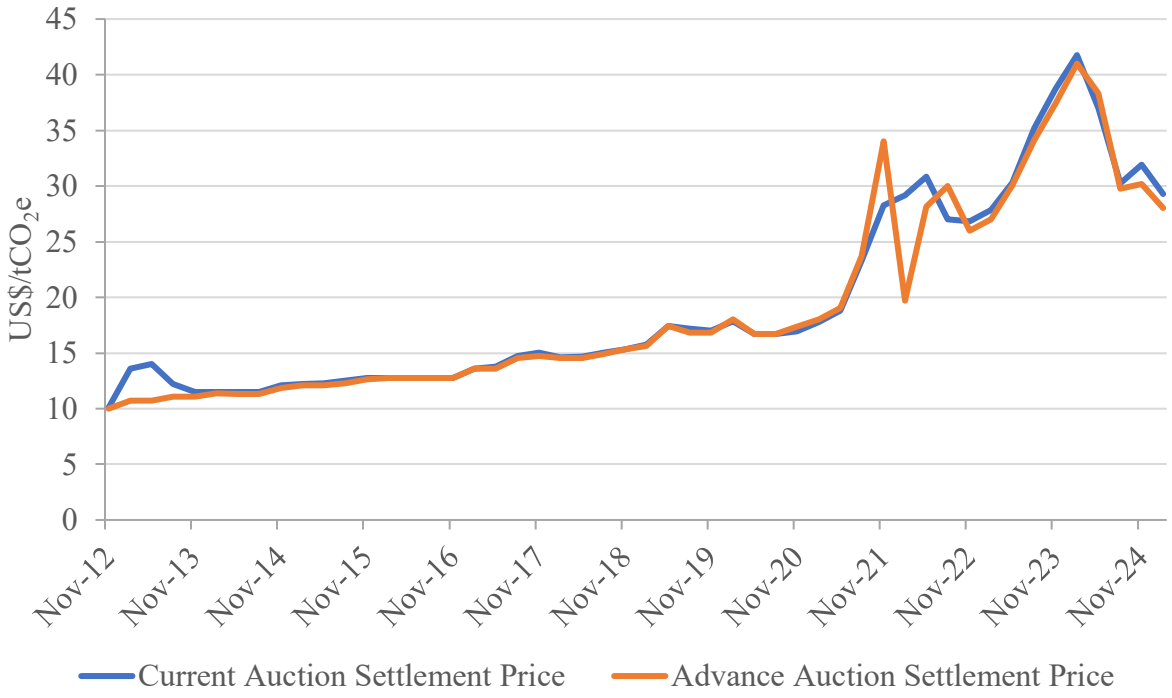

Figure 2. California Cap-and-Trade Program Auction Settlement Prices from November 2012–February 2025.

Note. Two types of allowances are offered for auctions: in the Current Auction, allowances for the current year; and in the Advance Auction, allowances for the third year into the future.

Source: CARB (2025b)