

CARBON FARMING IN KAZAKHSTAN

Interim Findings on Mitigation Potential of Agricultural Greenhouse Gas Emissions in Four Pilot Regions



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List of Acronyms and Symbols

Symbol	Description	Unit
AFOLU	Agriculture, Forestry and Other Land Use sector	-
AIFC	Astana International Financial Centre	-
BIO	Microbial Biomass	-
DPM	Decomposable Plant Material	-
ET ₀	Reference Evapotranspiration	mm
ETS	Emissions Trading System	-
GSOC-MRV	Global Soil Organic Carbon Monitoring, Reporting, and Verification	-
HUM	Humified Organic Matter	-
IOM	Inert Organic Matter	-
IPCC	Intergovernmental Panel on Climate Change	-
MAOC	Mineral-associated organic carbon	-
MENR	Ministry of Ecology and Natural Resources	-
MRV	Monitoring, Reporting, and Verification	-
NASA NEX-GDDP-CMIP6	NASA Earth Exchange Global Daily Downscaled Projections	-
NDC	Nationally Determined Contribution	-
OECD	Organisation for Economic Co-operation and Development	-
POC	Particulate organic carbon	-
RPM	Resistant Plant Material	-
SSP	Shared Socioeconomic Pathways	-
SOC	Soil organic carbon	mass-%
VCM	Voluntary carbon market	-

1 Background and Objectives

The Agriculture, Forestry and Other Land Use (AFOLU) sector is responsible for approximately one third of global greenhouse gas emissions (IPCC, 2023). At the same time, soils represent the largest terrestrial carbon pool, sequestering nearly four times as much carbon as above-ground biomass and twice as much as the atmosphere (Scharlemann et al., 2014; Zomer et al., 2017). Depending on management practices, soils can act as either carbon sources or sinks. Extensive research demonstrates that soil management techniques – such as the use of organic fertilizers, intercropping, mulching, conservation tillage, agroforestry, and diverse crop rotation systems – can significantly increase the organic carbon content of agricultural soils (Paustian et al., 2016; Smith et al., 2007).

Beyond carbon sequestration, carbon farming delivers a range of economic, environmental, and social benefits (Tang et al., 2016). These include reduced risk of yield loss (Droste et al., 2020), enhanced resilience to drought and heavy rainfall (Hamidov et al., 2018), more efficient nutrient use, and increased soil biodiversity. The ongoing global expansion of agricultural production has profound impacts on carbon, water, and nutrient cycles (Bondeau et al., 2006; Feddema et al., 2005; Foley et al., 2005), with far-reaching environmental consequences – particularly in terms of greenhouse gas emissions and habitat loss.

Kazakhstan ranks seventh globally in terms of organic carbon stocks in agricultural soils. Through adapted farming practices, the country's soils could sequester an additional 13-27 megatons of carbon annually, placing Kazakhstan 16th worldwide in terms of sink potential (Zomer et al., 2017). This positions Kazakhstan as an ideal candidate for carbon farming, with the potential to become a significant global carbon sink. Realising this potential, however, requires greater awareness among farmers regarding climate change and carbon farming, as well as the development of incentive schemes that reward carbon-enhancing agricultural practices.

The CarbonIQ pilot study seeks to establish a decision-making foundation for the feasibility of carbon farming in Kazakhstan as a vital environmental protection and climate change mitigation technology. The project's core objectives are to assess the carbon storage potential of Kazakh soils, estimate their capacity, and analyse key impacts – such as the promotion of biodiversity. In doing so, CarbonIQ explores opportunities for both ecological and economic transformation within the country's agricultural sector. The project also supports economic sustainability by demonstrating how soil carbon storage can benefit both nature and farmers' incomes. Additionally, CarbonIQ investigates the potential for carbon certificates to incentivize practices that enhance soil organic carbon and assesses the prospects for carbon trading in Kazakhstan.

To achieve these goals, the project addresses the following key questions:

- **Potential Assessment:** What is the actual carbon storage potential of agricultural soils in Kazakhstan?

- **Capacity Assessment:** What knowledge and technology are currently available in Kazakhstan to establish carbon farming, and where are the most urgent needs for action?
- **Pilot Sites:** How practical are theoretical approaches when implemented in the field?
- **Governance Mechanisms:** How can the development of soil organic matter in arable soils be reliably and representatively monitored? What compensation models can attract farmers to carbon farming, and what legal frameworks are needed to establish it?
- **Income Model:** Can carbon farming create a new income stream for farmers?

This report presents interim findings on the mitigation potential of agricultural greenhouse gas emissions in four pilot regions, focusing on the following key objectives:

1. **Calculation of CO₂ Storage Capacity (for Pilot Sites):** Determine the CO₂ storage capacity of the designated areas (as a forecast), taking into account factors such as soil properties, agricultural management, and climate.
2. **Calculation of Greenhouse Gas Emission Reduction Potential (for Pilot Sites):** Estimate the reduction in greenhouse gas emissions achievable through carbon farming applications in the designated areas (as a forecast).

This report should be read as a pilot-scale follow-up to the broader CarbonIQ publication set. While the Policy Brief formulates the strategic priorities and the Background & Technical Paper (Çeltikoğlu et al., 2025) provides the national technical and policy framework, the present report focuses on how these broader principles are applied at field level in four pilot regions. Its purpose is therefore not to restate the national framework, but to document first pilot-based observations, calculations, and methodological lessons related to CO₂ storage capacity and greenhouse gas mitigation potential under real farming conditions.

In this sense, the report serves as an interim implementation and results document. It translates the broader CarbonIQ approach into site-specific evidence from Qostanai, North Kazakhstan, Pavlodar, and Akmola, and it highlights both the opportunities and the current methodological limits of early-stage pilot monitoring. The results presented here should therefore be interpreted as a first analytical step toward a more robust regional and national MRV (monitoring, reporting, and verification) architecture, rather than as a final assessment of long-term mitigation performance.

2 Materials and Methods

This section describes how the general methodological principles outlined in the wider CarbonIQ framework were applied in the four pilot regions. Particular attention is given to site boundaries, baseline conditions, soil monitoring, first modelling steps, and the assessment of greenhouse gas mitigation pathways at farm level. The intention is to make transparent which elements are already based on pilot measurements and which elements still represent model-based or methodological approximations.

2.1 Study Region

2.1.1 Pilot Qostanai Region

The experimental site in Qostanai, located between 52°23'58.0"N and 62°11'21.2"E, encompasses 82.02 ha of land used for agriculture (Figure 1). According to the IPCC's land-use categories the experimental site is classified as cropland. It is managed under dry-farming conditions. The field lay fallow from 2021 to 2023. In 2024 red lentils (*Lens culinaris* Medikus) were grown and the soil was cultivated using a harrow (3 cm). In 2025 durum wheat (*Triticum durum*) was farmed and several carbon farming techniques were implemented. These comprise no till, growing cover crops as well as the use of biochar.

To understand the soil's characteristics, we took composite samples at two depths (0-30 and 30-60 cm) for subsequent laboratory analysis. We conducted these measurements in 2024 and 2025 before the crops were sown, as well as before and after harvest. The 2024 results established the baseline for our observation period.

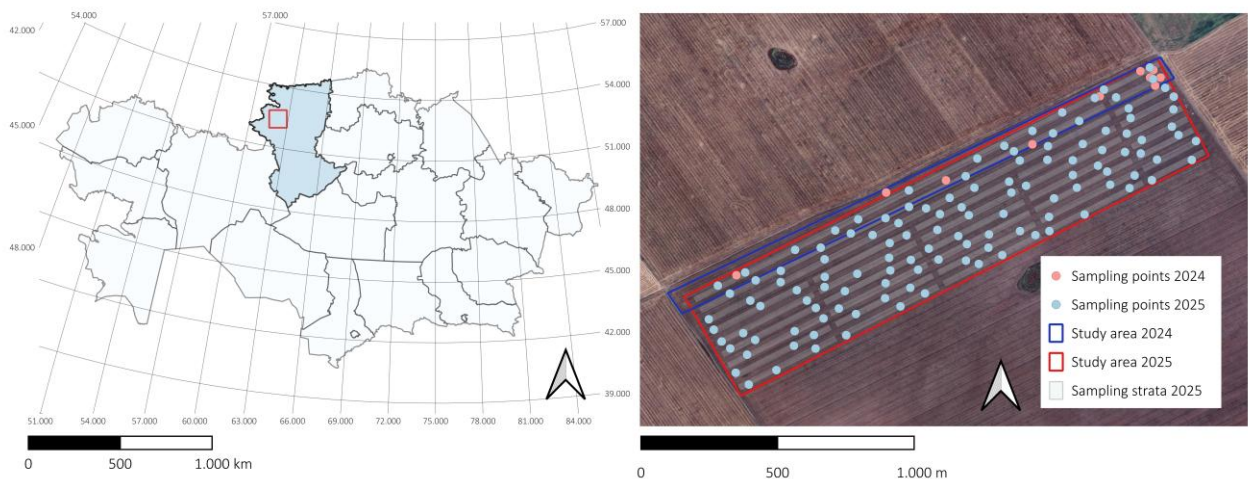


Figure 1: Location of the pilot site in Kazakhstan (left) and spatial distribution of sampling points within the study site in 2024 and 2025 (right).

2.1.2 Pilot North Kazakhstan Region

The experimental site in the North Kazakhstan Region located between 54°48'52"N and 68°4'34"E, encompasses 50 ha of land used for agriculture (Figure 2). According to the IPCC’s land-use categories the experimental site is classified as cropland. It is managed under dry-farming conditions. Rape seeds (*Brassica napus*) were grown in 2024. In 2021, 2022, and 2023 the following crops were grown: white wheat, barley, buckwheat, peas, flaxseed, rapeseed, sunflowers and haylage. In 2025, summer wheat (*Triticum aestivum* L.) was planted and the site was not tilled.

To understand the soil's characteristics, we took composite samples at two depths (0-30 and 30-60 cm) for subsequent laboratory analysis. We conducted these measurements in 2024 and 2025 before the crops were sown, as well as before and after harvest. The 2024 results established the baseline for our observation period.

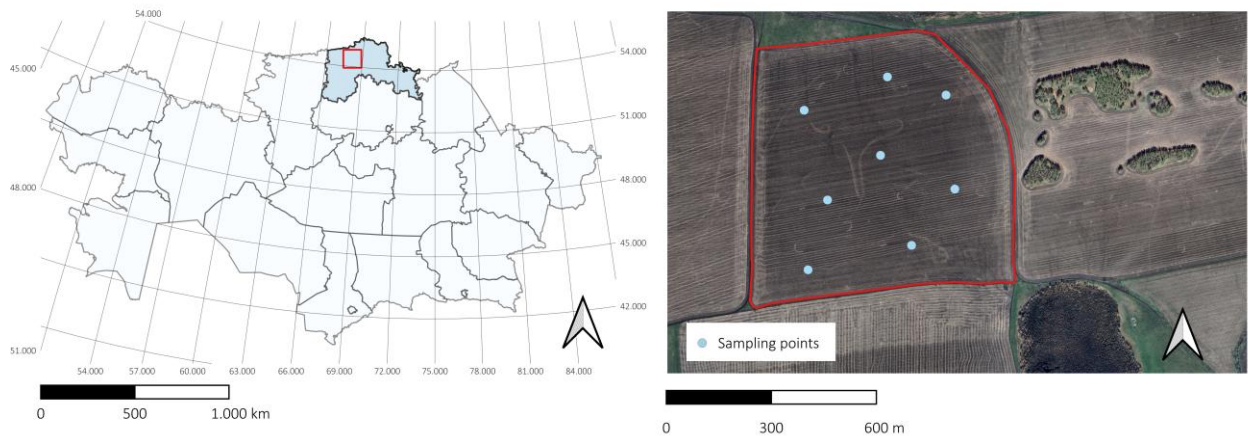


Figure 2: Location of the pilot site in Kazakhstan (left) and spatial distribution of sampling points within the study area (right).

2.1.3 Pilot Pavlodar Region

The experimental site in Pavlodar, located between 52°57'45.67"N and 75°50'30.71"E, encompasses 70.46 ha of land used for agriculture (Figure 3). According to the IPCC’s land-use categories the experimental site is classified as cropland. It is managed under dry-farming conditions and had remained fallow for over 5 years prior to recultivation. In 2024, common wheat (*Triticum aestivum*) was grown and in 2025, barley (*Hordeum vulgare*), potatoes (*Solanum tuberosum*) and common wheat (*Triticum aestivum*) were planted. The site was tilled in both 2024 and 2025.

To understand the soil's characteristics, we took composite samples at two depths (0-30 and 30-60 cm) for subsequent laboratory analysis. We conducted these measurements in 2024 and 2025 before the crops were sown, as well as before and after harvest. The 2024 results established the baseline for our observation period.

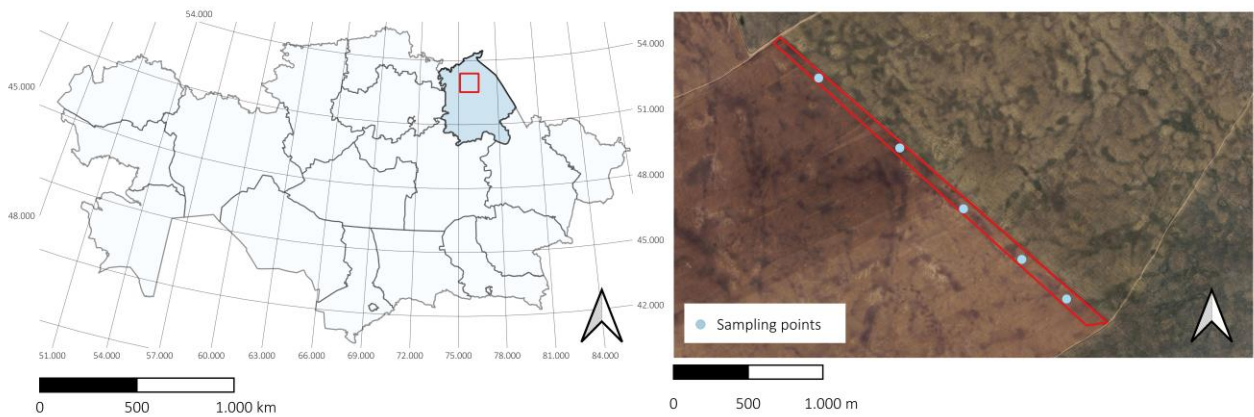


Figure 3: Location of the pilot site in Kazakhstan (left) and spatial distribution of sampling points within the study area (right).

2.1.4 Pilot Akmola Region

The experimental site in Akmola, located between 52°44'39.9"N and 70°46'12.4"E, encompasses 21.08 ha of land used for agriculture (Figure 4). According to the IPCC's land-use categories the experimental site is classified as cropland. It is managed under dry-farming conditions. The site had lain fallow for more than 5 years. In October 2023, the soil was tilled with a cultivator to a depth of 18 cm. In 2024, common wheat (*Triticum aestivum*) was grown, followed by green lentils (*Lens culinaris* Medikus) in 2025.

To understand the soil's characteristics, we took composite samples at two depths (0-30 and 30-60 cm) for subsequent laboratory analysis. We conducted these measurements in 2024 and 2025 before the crops were sown, as well as before and after harvest. The 2024 results established the baseline for our observation period.

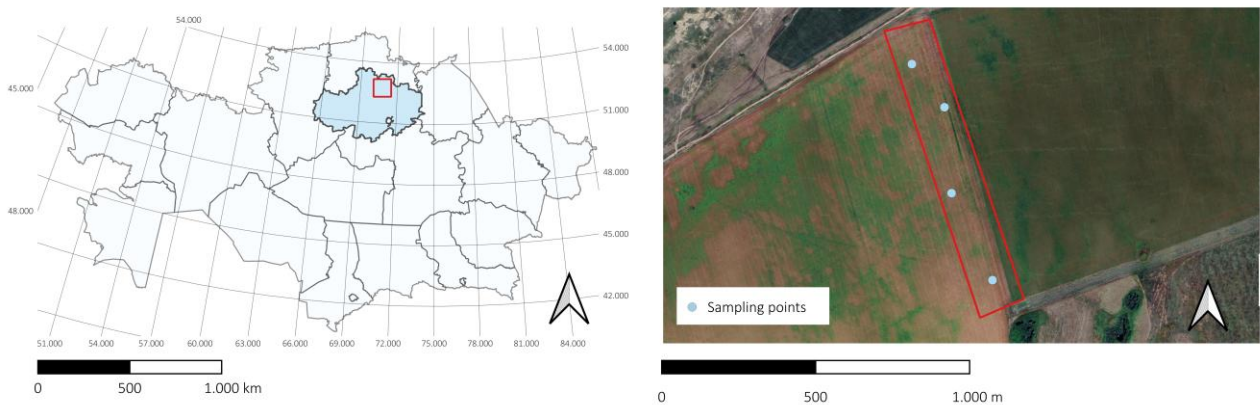


Figure 4: Location of the pilot site in Kazakhstan (left) and spatial distribution of sampling points within the study area (right).

2.2 Methods

2.2.1 Soil Organic Carbon Monitoring

Soil organic carbon monitoring in the four pilot regions combines field-based screening with laboratory-based reference analysis. The sampling design follows a stratified approach in line with the GSOC-MRV logic (Global Soil Organic Carbon Monitoring, Reporting and Verification), with the aim of achieving representative coverage of each pilot field while avoiding border effects and major internal bias (FAO, 2020). North Kazakhstan, Akmola, and Pavlodar were each treated as single homogeneous sampling units because their plots show relatively uniform management and soil conditions. In contrast, the Qostanai site was subdivided into several blocks because additional field experiments were implemented there, including different carbon farming treatments such as no-till, low-till, and biochar application. The following operational details further specify how this monitoring approach was implemented in practice at field level.

For the quantitative assessment of SOC and related soil properties, physical soil samples were collected and analysed in the laboratory. In this sense, the laboratory results represent the reference dataset for the present report, while the handheld measurements serve as supportive contextual information. Laboratory sampling was conducted at two depth intervals, 0-30 and 30-60 cm, using composite samples made up of several subsamples collected in close proximity and homogenised before analysis. This design was chosen to reflect the current pilot setup and to allow a first comparison between baseline and repeated measurements under real field conditions. At the same time, it should be noted that future integration into a broader national MRV platform may require a deeper sampling design, for example extending to 100 cm depth where feasible, in order to improve comparability with wider soil-carbon monitoring frameworks. SOC stocks were calculated by combining laboratory-based SOC concentrations with bulk density measurements for each depth interval and then summing both strata to represent the upper 60 cm of soil. At this stage, the calculations are based on fixed depth intervals and should be interpreted as pilot-scale stock estimates within the current monitoring design. An overview over all variables measured in the laboratory provides Table 1.

Table 1: Soil physical and chemical variables measured in the laboratory.

Parameter	Unit	Method & Standard
Nitrate-nitrogen (N-NO ₃ ⁻)	mg kg ⁻¹	GOST 26488-85
Phosphorus pentoxide (P ₂ O ₅)	mg kg ⁻¹	Machigin method – GOST 26205-91 Chirikov method – GOST 26204-91
Potassium oxide (K ₂ O)	mg kg ⁻¹	Machigin method – GOST 26205-91 Chirikov method – GOST 26204-91
Soil organic matter (SOM)	%	GOST 26213-91
Soil organic carbon (SOC)	%	Dumas combustion method
pH	-	GOST 26423-85
Electrical conductivity (EC)	mS cm ⁻¹	GOST 26423-85

2.2.2 Soil Organic Carbon Modelling

To complement field measurements, a preliminary modelling framework was developed to interpret soil organic carbon (SOC) dynamics beyond the currently limited monitoring period. This work is based on the RothC model (Coleman & Jenkinson, 1996), which simulates SOC turnover as a function of climate, soil properties, and management practices. Within the scope of this report, the model is not intended to generate fixed long-term forecasts but to provide indicative trajectories of SOC development under observed management conditions at the pilot sites, combined with climate change scenarios.

The model parameterisation relies on site-specific data from the pilot regions, including baseline SOC values, soil depth, crop management, and available climatic inputs. Given the short duration of the current monitoring period, calibration should be considered provisional. Consequently, modelling outputs are used primarily to support interpretation and forward-looking discussions, particularly regarding cumulative SOC storage potential over time. Projections should be interpreted as indicative technical pathways under stable management assumptions, rather than as definitive annual outcomes.

In alignment with the broader CarbonIQ methodology, this modelling approach represents one component of an integrated evidence system that combines field sampling, laboratory analysis, and – at later stages – remote sensing and advanced Tier 2-3 upscaling techniques. At this stage, the purpose of modelling is to link initial pilot measurements with plausible medium-term development trends and to clarify the assumptions underlying these trends. In this report, RothC serves primarily as an interpretative and preparatory tool. Site-specific forward projections should be regarded as provisional until harmonized climate, soil, and management inputs are consistently available across all pilot regions.

RothC comprises five soil carbon compartments: four active compartments – Decomposable Plant Material (DPM), Resistant Plant Material (RPM), Microbial Biomass (BIO), and Humified Organic Matter (HUM) – and

the Inert Organic Matter (IOM) compartment, which represents the clay-associated and decomposition-resistant carbon fraction. While IOM stocks were calculated using Falloon's method (Falloon et al., 1998), no data were available for the active carbon compartments or carbon inputs. These parameters were determined using the "inverse RothC" method, an iterative initialisation process where assumed carbon inputs are adjusted until the modelled equilibrium SOC matches empirical measurements (Wiltshire & Bekege, 2022; Wiltshire et al., 2023). As only the Qostanai Region Pilot has sufficient sampling size to reliably calculate average SOC stock, predictions were limited to this site in the report.

Climate forcing during the spin-up was parameterised using time series (1995-2023) of monthly averaged temperature, precipitation, and ETO data from the ERA5 (Hersbach et al., 2023) dataset for the grid cell containing the Qostanai Region Pilot. This climate data was iterated 40 times to create a sufficiently long time series for the model to reach compartment equilibrium. Management options were parameterised with a rate-modifying factor of 1 for conventional tillage and 0.6 for covered soil during the vegetation period (May-September), and 1 for all other months, following RothC specifications (Coleman & Jenkinson, 1996). The entire model setup was iterated with varying carbon inputs until the sum of all SOC compartments at equilibrium matched observed SOC stocks.

The equilibrium stocks for each compartment were then used as initial conditions to predict SOC stocks until 2100, using temperature, precipitation, and ET_0 (reference evapotranspiration) projections from three climate change scenarios (Shared Socioeconomic Pathways) as defined in the IPCC Sixth Assessment Report (IPCC, 2023):

- **SSP1-2.6:** Low greenhouse gas emissions, with CO_2 emissions reaching net zero around 2075; projected warming of 1.6°C (2041-2060) and 1.4°C (2081-2100).
- **SSP2-4.5:** Intermediate emissions, with CO_2 levels remaining near current values until 2050 before declining but not reaching net zero by 2100; projected warming of 2.0°C (2041-2060) and 2.7°C (2081-2100).
- **SSP5-8.5:** Very high emissions, with CO_2 emissions tripling by 2075; projected warming of 2.4°C (2041-2060) and 4.4°C (2081-2100).

Climate data for these scenarios were sourced from the NASA NEX-GDDP-CMIP6 dataset (NASA, 2026) for the grid cell containing the Qostanai Region Pilot. In addition to the climate scenarios, two management scenarios were parameterised:

- **Conventional:** Uses the same management options as in the spin-up, with a rate-modifying factor of 1 for conventional tillage and 0.6 for covered soil during the vegetation period (May-September), and 1 for all other months.
- **Carbon farming:** Uses a rate-modifying factor of 0.93 for reduced tillage (Jordon & Smith, 2022) and 0.6 for covered soil throughout the entire year, simulating the effects of crop residues and cover crops.

Each climate change scenario was combined with each management scenario, resulting in six distinct model setups to project SOC stock development until 2100. All other RothC parameters were retained at their default values. The model was implemented using the SoilR package (Sierra et al., 2014) within the RStudio environment (Posit team, 2026).

2.2.3 Assessing Greenhouse Gas Flux Balances

The assessment of greenhouse gas mitigation potential in this report follows a net-balance logic. In addition to changes in soil organic carbon stocks, the analysis considers relevant non-CO₂ effects where sufficiently reliable information is available. In practical terms, this includes the potential reduction of direct and indirect N₂O emissions from lower mineral nitrogen input, CO₂ emissions associated with urea application, and selected energy-related CO₂ effects linked to changes in field operations such as reduced tillage intensity or reduced machinery use.

The analytical scope remains intentionally conservative. Not all components can currently be quantified with the same level of certainty across all four pilot sites. For this reason, the report distinguishes between effects that can already be discussed on the basis of available pilot data and effects that remain indicative or qualitative at this stage. This is especially relevant for non-CO₂ emissions, where robust quantification depends on sufficiently detailed fertiliser logs, field management records, and consistent activity data.

Methodologically, the assessment is aligned with the logic of the FAO GSOC-MRV Protocol (2020) and the IPCC AFOLU framework (IPCC, 2019). However, the present report does not claim to provide a full crediting-ready emissions inventory. Rather, it offers a pilot-based first estimate of the main mitigation pathways associated with the tested carbon farming practices and identifies where further data collection will be needed for more robust future accounting.

The annual values used for mineral nitrogen fertiliser, urea, machinery use, and fuel consumption are not directly measured and fully verified plot-level field records. Instead, they were reconstructed as regionally plausibilised annual field activity data. This reconstruction is based on three layers of evidence: expert feedback from the pilot regions, the known management history of the pilot sites (e.g. crop type, fallow periods, tillage or no-till systems, cover crops, and biochar application), and available regional comparison and plausibility information. Additional benchmark information from northern Kazakhstan further indicates that dryland cereal systems are typically shaped by region-specific fertiliser combinations as well as characteristic fuel and machinery requirements for sowing, chemical treatment, harvesting, and, where relevant, tillage operations. The resulting values should therefore be understood as regionally supported expert guideline values rather than as auditable primary data.

This procedure is scientifically defensible because the report explicitly treats the assessment of greenhouse gas mitigation pathways as a first pilot-based estimate rather than a full crediting-ready emissions inventory. The FAO GSOC-MRV Protocol requires activity data for baseline and intervention scenarios, including crops, tillage, fertiliser application, machinery use, and fuel consumption, but also allows for a transparent and conservative use of regionally typical management information where complete plot-level records are not yet available (FAO, 2020). Accordingly, the values used here for 2024–2025 are treated as reconstructed

annual field activity data based on regional expert estimates and plausibility checks. They provide a realistic and methodologically cautious basis for the initial quantification of mitigation pathways, but they do not replace fully verified field records.

Specifically, the reduction of GHG emissions by reduced application of N-fertilisers and urea as well as by fuel savings is calculated with the formulas provided by IPCC (2019). N₂O emissions from mineral N-fertilisers are calculated as follows:

$$N_2O_{emissions} (kg CO_2eq ha^{-1}) = N_{applied}(kg ha^{-1}) * 0.01 * 265$$

N₂O emissions from mineral nitrogen fertilisers are typically calculated using the IPCC emission factor of 1% of applied N (or 0.01 kg N₂O-N per kg N applied). The global warming potential (GWP) of N₂O is 265 kg CO₂e per kg N₂O-N.

CO₂ emissions from urea are calculated as follows:

$$CO_2_{emissions} (kg CO_2 ha^{-1}) = Urea_{applied}(kg ha^{-1}) * 0.2$$

Urea application emits CO₂ directly due to its chemical composition. The emission factor is 0.2 kg CO₂ per kg urea applied.

CO₂ emissions from fuel are calculated as follows:

$$CO_2_{emissions} (kg CO_2 ha^{-1}) = Fuel_{used}(L ha^{-1}) * 2.68$$

Fuel use in agriculture emits CO₂ (and indirectly N₂O and CH₄). The emission factor for diesel is according to IPCC 2.68 kg CO₂ per litre.

Table 2 summarises reconstructed annual application rates of mineral N-fertilisers, urea, and fuel consumption used as input data for the pilot-based assessment of greenhouse gas mitigation pathways.

Table 2: Annual application rates of mineral N-fertilisers, urea, and fuel consumptions averaged for the four Pilots. Years with values of 0 indicate fallow conditions in the respective year.

Pilot	Year	Mineral N-fertiliser	Urea-N input	Fuel consumption
(-)	(-)	(kg ha ⁻¹)	(kg ha ⁻¹)	(L ha ⁻¹)
Qostanai	2023	0	0	0
	2024	20	0	12
	2025	40	40	12
North Kazakhstan	2023	25	0	10
	2024	35	0	11
	2025	20	0	10
Akmola	2023	0	0	8
	2024	40	0	15
	2025	0	0	10
Pavlodar	2023	0	0	0
	2024	35	0	18
	2025	40	10	22

Reference values from German field trials (Meister et al., 2025) were used to calculate emission reduction by carbon farming practices. This study found that changing agricultural management from tillage to no-till farming reduced fuel consumption by 75%. On average across all crops, the application of mineral N-fertilisers could be reduced by 15% by shifting from conventional to conservation agriculture.

2.2.4 Assumptions and Possible Restrictions

This report is based on an early monitoring phase and must therefore be interpreted within a clearly defined set of methodological boundaries. First, the available time series is still short. In most cases, the current comparison covers only the baseline year and one repetition of sampling. As a result, observed differences between campaigns cannot yet be interpreted as firm long-term management effects. Natural variability, sampling artefacts, and differences in local field conditions remain plausible explanatory factors, especially where the observed annual changes are unusually large.

Second, the current pilot setup is not fully uniform across all regions. Sampling intensity, field history, and treatment structure differ between sites, and in the case of Qostanai the expansion of the sampling area between 2024 and 2025 affects direct comparability between campaigns. Third, the present assessment focuses primarily on technical potential under pilot conditions. It does not represent a credit issuance assessment and should not be interpreted as evidence that the observed or modelled outcomes are already directly transferable into compliance-based carbon units.

More generally, all quantitative values in this report should be read as indicative and context-specific. This applies in particular to cumulative CO₂-equivalent values and to any medium-term projection of SOC development. Soil carbon dynamics are inherently heterogeneous, respond slowly to management, and are shaped by climatic and pedological conditions that vary across the pilot regions. For this reason, conservative interpretation, transparent uncertainty communication, and longer-term resampling remain essential for future reporting.

3 Results

3.1 Observed SOC Stocks

3.1.1 Pilot Qostanai Region

The baseline average soil organic carbon concentrations, as determined in 2024, are 1.48 ± 0.26 mass-% in the upper stratum (0-30 cm) and 1.16 ± 0.29 mass-% in the lower stratum (30-60 cm) at the experimental site in the Qostanai Region (Figure 5). The first repetition of sampling in 2025 revealed values that were 40-50% higher: 2.05 ± 0.22 mass-% for the upper stratum and 1.73 ± 0.23 mass-% for the lower stratum. However, this increase is due to the expansion of the sampling area between campaigns and the consequent 15-fold increase in sampling size (10 sites sampled in 2024 versus 150 sites sampled in 2025 at each depth). As such, the 2025 results represent a much larger area, including spots with higher SOC concentrations, than was sampled in 2024. Therefore, the two campaigns cannot be compared with regard to the effect of carbon farming practices on SOC. Compared to reference samples, the determined values are 0.5 mass-% below the average value (2.6 mass-%) for chernozem soil in the Qostanai region, as reported by Zharlygassov et al. (2025), for the upper stratum. No literature references could be found for the lower stratum.

The calculated baseline SOC stocks were 53 ± 9.15 Mg ha⁻¹ for the upper stratum and 48.30 ± 12.22 Mg ha⁻¹ for the lower stratum in 2024. Consistent with the higher SOC concentrations observed in the comparison between the baseline and the first repetitions, the stocks in 2025 are also higher, at 74.41 ± 8.01 and 72.07 ± 9.36 Mg ha⁻¹ for the upper and lower strata, respectively. Summing both strata gives calculated SOC stocks of 146.48 ± 12.33 Mg ha⁻¹ within the upper 60 cm of soil at the experimental site in the Qostanai Region in 2025. Converted to CO₂, this pool equates to 537 Mg CO₂ ha⁻¹ or 44,056 Mg CO₂ if scaled to the entire experimental site (82.02 ha).

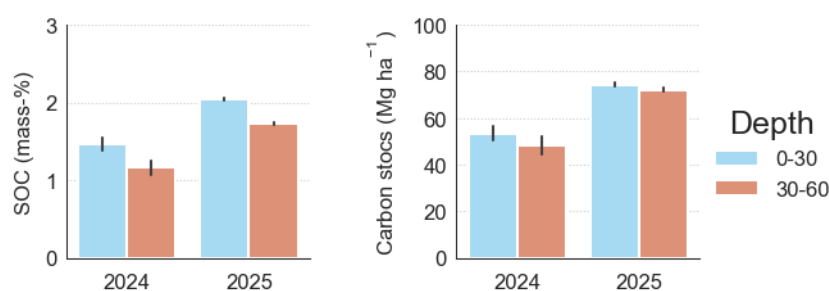


Figure 5: Lab-determined soil organic carbon (SOC) concentrations (mass-%, left) and calculated SOC stocks (Mg ha⁻¹, right) at the Qostanai Region experimental site. Data are stratified by soil depth and sampling campaigns, with sample sizes of n = 10 (2024) and n = 150 (2025). Error bars indicate the standard error of the mean.

3.1.2 Pilot North Kazakhstan Region

The baseline average soil organic carbon concentrations, as determined in 2024, are 2.13 ± 0.48 mass-% in the upper stratum (0-30 cm) and 1.97 ± 0.49 mass-% in the lower stratum (30-60 cm) at the experimental

site in the North Kazakhstan Region (Figure 6). The first repetition of sampling in 2025 revealed values that were 6-16% higher: 2.46 ± 0.21 mass-% for the upper stratum and 2.10 ± 0.39 mass-% for the lower stratum. This increase signifies a total SOC gain of 0.34 and 0.13 mass-% for the upper and lower strata within one year on average. Such an increase is above the typical range of SOC increases of 0.01-0.05 mass-% year⁻¹ reported by a global meta-analysis on the effect of improved cropland management practices in semi-arid settings (Lessmann et al., 2022). However, as our monitoring period has only covered one year thus far, it is not possible to definitively attribute the observed SOC increase to carbon farming practices, as it could also be explained by sampling artefacts and differing boundary conditions between sampling campaigns. Typically, the effects of carbon farming require 3–5 years of improved cropland management to detect changes in SOC against natural variability.

The calculated baseline SOC stocks were 74.25 ± 16.79 Mg ha⁻¹ for the upper stratum and 81.16 ± 20.11 Mg ha⁻¹ for the lower stratum in 2024. As the SOC concentrations in the upper and lower strata are close-by, the higher stock in the lower stratum is due to its higher bulk density. In line with the higher SOC concentrations observed in the comparison between the baseline and the first repetitions, the stocks in 2025 are also higher, at 85.72 ± 7.24 and 86.52 ± 16.27 Mg ha⁻¹ for the upper and lower strata, respectively. Summing both strata gives calculated baseline SOC stocks of 155.41 ± 26.19 Mg ha⁻¹ within the upper 60 cm of soil at the experimental site in the North Kazakhstan Region in 2024. Converted to CO₂, this pool equates to 570 Mg CO₂ ha⁻¹ or 28,494 Mg CO₂ if scaled to the entire experimental site (50 ha).

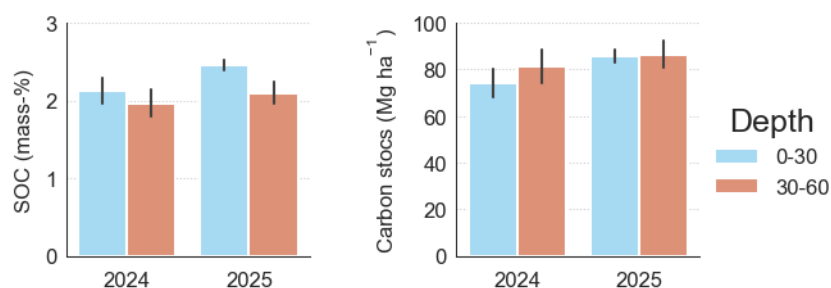


Figure 6: Lab-determined soil organic carbon (SOC) concentrations (mass-%, left) and calculated SOC stocks (Mg ha⁻¹, right) at the North Kazakhstan Region experimental site. Data are stratified by soil depth and sampling campaigns, with sample sizes of n = 8. Error bars indicate the standard error of the mean.

3.1.3 Pilot Pavlodar Region

The baseline average soil organic carbon concentrations, as determined in 2024, are 0.98 ± 0.32 mass-% in the upper stratum (0-30 cm) and 0.78 ± 0.18 mass-% in the lower stratum (30-60 cm) at the experimental site in the Pavlodar Region (Figure 7). A large-scale study across Kazakhstan found that topsoil SOC in the northern steppe regions (including Pavlodar) typically ranges from about 0.5-1.5 mass-%, with higher values in less disturbed or native steppe soils and lower values in intensively cropped or degraded land (Yapiyev et al., 2025). As such the Pavlodar site rather reflects degraded soil conditions due to long-term intensive agricultural usage. The first repetition of sampling in 2025 revealed values that were 7-20% lower: 0.78 ± 0.18 mass-% for the upper stratum and 0.37 ± 0.09 mass-% for the lower stratum. This reduction signifies a total SOC loss of 0.19 and 0.02 mass-% for the upper and lower strata within one year on average.

However, as our monitoring period has only covered one year thus far, it is not possible to definitively attribute the observed SOC decrease to carbon farming practices, as it could also be explained by sampling artefacts and differing boundary conditions between sampling campaigns. Typically, the effects of carbon farming require 3-5 years of improved cropland management to detect changes in SOC against natural variability.

The calculated baseline SOC stocks were $35.75 \pm 11.87 \text{ Mg ha}^{-1}$ for the upper stratum and $16.33 \pm 4.69 \text{ Mg ha}^{-1}$ for the lower stratum in 2024. In line with the lower SOC concentrations observed in the comparison between the baseline and the first repetitions, the stocks in 2025 are also lower, at 28.52 ± 6.68 and $15.17 \pm 4.08 \text{ Mg ha}^{-1}$ for the upper and lower strata, respectively. Summing both strata gives calculated baseline SOC stocks of $52.09 \pm 12.87 \text{ Mg ha}^{-1}$ within the upper 60 cm of soil at the experimental site in the Pavlodar Region in 2024. Converted to CO_2 , this pool equates to $191 \text{ Mg CO}_2 \text{ ha}^{-1}$ or $13,457 \text{ Mg CO}_2$ if scaled to the entire experimental site (70.46 ha).

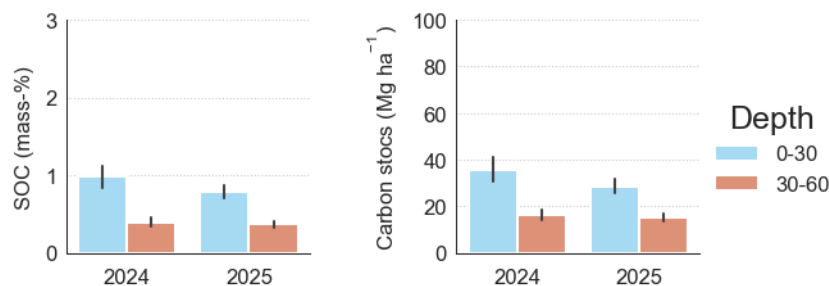


Figure 7: Lab-determined soil organic carbon (SOC) concentrations (mass-%, left) and calculated SOC stocks (Mg ha^{-1} , right) at the Pavlodar Region experimental site. Data are stratified by soil depth and sampling campaigns, with sample sizes of $n = 5$. Error bars indicate the standard error of the mean.

3.1.4 Pilot Akmola Region

The baseline average soil organic carbon concentrations (SOC), as determined in 2024, are $1.98 \pm 0.28 \text{ mass-}\%$ in the upper stratum (0-30 cm) and $1.25 \pm 0.26 \text{ mass-}\%$ in the lower stratum (30-60 cm) at the experimental site in the Akmola Region (Figure 8). The first repetition of sampling in 2025 revealed values that were 2% higher in the upper stratum ($2.03 \pm 0.36 \text{ mass-}\%$) and 8% lower in the lower stratum ($1.15 \pm 0.23 \text{ mass-}\%$). This increase signifies a total SOC gain of 0.05 mass-% for the upper stratum within one year on average. Such a gain lies at the upper limit of the typical range of SOC increases ($0.01\text{-}0.05 \text{ mass-}\% \text{ year}^{-1}$) reported by a global meta-analysis on the effect of improved cropland management practices in semi-arid settings (Lessmann et al., 2022). However, since monitoring has covered only one year so far, it is not possible to definitively attribute the observed SOC increase to carbon farming practices. It could also result from sampling artefacts or variations in boundary conditions between campaigns. Typically, several years (3-5) of improved cropland management are required before changes in SOC become distinguishable from natural variability. Likewise, the observed decrease of 0.1 mass-% in the lower stratum remains ambiguous and may reflect either management-induced effects or natural fluctuations.

The calculated baseline SOC stocks were $69.44 \pm 9.91 \text{ Mg ha}^{-1}$ for the upper stratum and $53.17 \pm 11.17 \text{ Mg ha}^{-1}$ for the lower stratum in 2024. In line with the changes in SOC concentrations in the in the comparison between the baseline and the first repetitions, the stocks in 2025 increased in the upper stratum and decreased in the lower stratum (71.01 ± 12.66 and $48.82 \pm 9.69 \text{ Mg ha}^{-1}$, respectively). Summing both strata gives calculated baseline SOC stocks of $122.61 \pm 14.93 \text{ Mg ha}^{-1}$ within the upper 60 cm of soil at the experimental site in the Akmola Region in 2024. Converted to CO_2 , this pool equates to $449.60 \text{ Mg CO}_2 \text{ ha}^{-1}$ or $9,477 \text{ Mg CO}_2$ if scaled to the entire experimental site (21.08 ha).

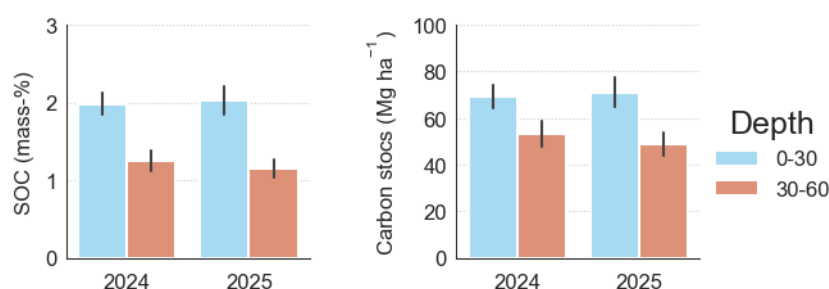


Figure 8: Lab-determined soil organic carbon (SOC) concentrations (mass-%, left) and calculated SOC stocks (Mg ha^{-1} , right) at the Akmola Region experimental site. Data are stratified by soil depth and sampling campaigns, with sample sizes of $n = 4$. Error bars indicate the standard error of the mean.

3.1.5 Overall Evaluation

The cross-site comparison should be read on three levels: baseline SOC status, short-term changes between 2024 and 2025, and the cautious interpretation of current stocks in relation to possible future sequestration under continued management.

The four pilot sites – Qostanai, North Kazakhstan, Pavlodar, and Akmola – demonstrate marked differences in baseline SOC concentrations and stocks, reflecting regional variations in soil type, land use history, and management practices. Qostanai and Pavlodar represent the extremes (Figure 9): Qostanai’s and Pavlodar’s baseline SOC values (1.48 ± 0.26 and 0.98 ± 0.32 mass-% within the upper 30 cm of soil, respectively) fall below the regional average (Zharlygassov et al., 2025), indicate degraded conditions due to long-term intensive agriculture. In contrast, North Kazakhstan and Akmola exhibit higher baseline SOC concentrations (2.13 ± 0.48 mass-% and 1.98 ± 0.28 mass-% in the upper stratum, respectively), consistent with less disturbed or better-managed soils.

All sites experienced changes in SOC concentrations and stocks between 2024 and 2025, though the direction and magnitude of these changes vary significantly. North Kazakhstan and Akmola recorded increases in SOC concentrations (6-16% and 2-8%, respectively), with North Kazakhstan’s gains exceeding the typical range reported in global meta-analyses for improved cropland management in semi-arid settings (Lessmann et al., 2022). Conversely, Pavlodar saw a notable decrease in SOC (7-20%), likely reflecting ongoing degradation or sampling variability. The apparent 40-50% increase in Qostanai is attributable to an expanded sampling area and increased sample size, rather than a genuine change in SOC. The observed changes across all sites cannot yet be definitively attributed to carbon farming practices, as natural

variability and sampling artefacts remain plausible explanations after only one year of monitoring. Typically, the effects of improved management require three to five years to become distinguishable from natural fluctuations.

Cumulative SOC stocks within the upper 60 cm of soil range from $52.09 \pm 12.87 \text{ Mg ha}^{-1}$ in Pavlodar to $155.41 \pm 26.19 \text{ Mg ha}^{-1}$ in North Kazakhstan, corresponding to CO_2 equivalents of $191\text{-}570 \text{ Mg CO}_2 \text{ ha}^{-1}$. When scaled to the entire experimental areas, the currently measured SOC stock expressed as CO_2 -equivalent varies widely, from $9,477 \text{ Mg CO}_2$ in Akmola (21.08 ha) to $44,056 \text{ Mg CO}_2$ in Qostanai (82.02 ha).

At the same time, it is important to distinguish clearly between current SOC stocks and additional sequestration potential. The stock values measured or calculated for the upper 60 cm describe the present carbon pool in the soil under current conditions. They should not automatically be interpreted as the amount of additional carbon that can still be sequestered in the future. Where the report refers to future storage potential, this should be understood as a separate, model-based estimate that depends on management continuity, local soil conditions, and the gradual nature of soil-carbon accumulation.

In summary, these initial results underscore the importance of long-term monitoring and consistent sampling protocols. While early trends suggest potential for SOC sequestration in some regions, definitive conclusions will require at least three to five years of data to reliably distinguish management effects from natural variability.

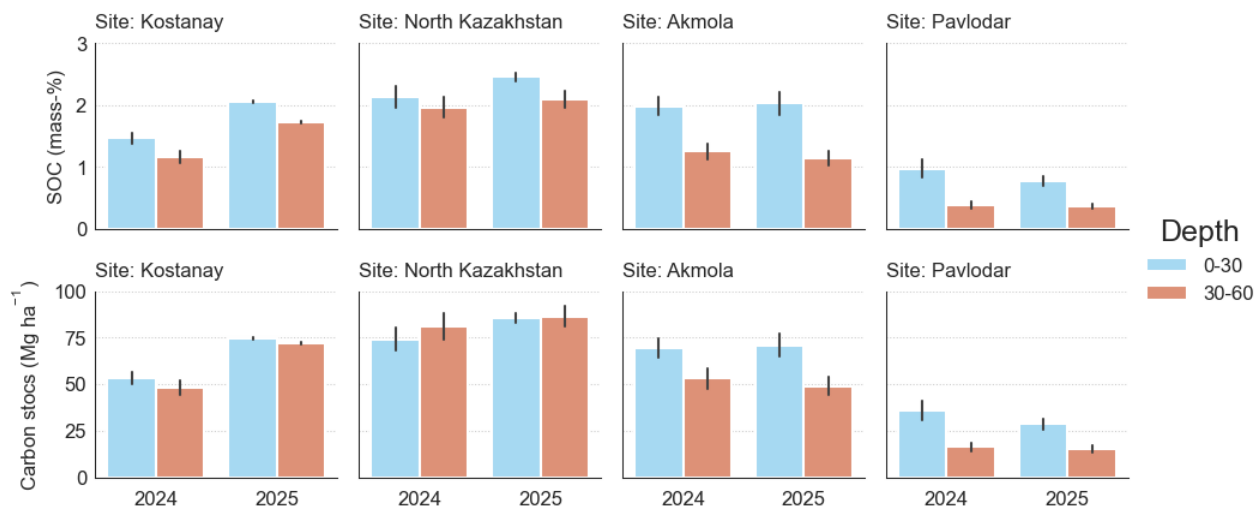


Figure 9: Lab-determined soil organic carbon (SOC) concentrations (mass-%, top row) and calculated SOC stocks (Mg ha^{-1} , bottom row) separated by experimental site. Data are stratified by soil depth and sampling campaigns, with differing sampling sizes (Qostanai: $n = 10$ (2024) and $n = 150$ (2025), North Kazakhstan: $n = 8$, Pavlodar: $n = 5$, Akmola: $n = 4$). Error bars indicate the standard error of the mean.

3.2 Modelled SOC Stocks

As no data on SOC contents for the five compartments required by RothC or carbon inputs were available, the model was run through a spin-up period. During this spin-up, all management parameters – including tillage, soil cover, and carbon input – were held constant, while climate boundary conditions were iterated

until the model reached equilibrium between carbon inputs and decomposition. Figure 10 illustrates the SOC dynamics over the 1,100-year spin-up period for the Qostanai Region Pilot. The temporal dynamics clearly distinguish the active compartments (DPM = Decomposable Plant Material, RPM = Residual Plant Material, BIO = Microbial Biomass, and HUM = Humified Organic Matter) from the decomposition-resistant and clay-associated Inert Organic Matter (IOM), which remains unchanged throughout the spin-up. After 1,000 years, total SOC stabilizes at 74 Mg ha⁻¹, matching observed field stocks and indicating equilibrated compartments. The carbon input required to achieve this equilibrium was parametrized at 1.89 Mg ha⁻¹ yr⁻¹. Such an extended spin-up is essential because the slowest-responding compartment, HUM, typically accumulates over decades to centuries, as reflected in the model (Figure 10). Literature commonly reports spin-up periods of at least 500 years (Geremew et al., 2024), though some studies recommend up to 10,000 years (Nemo et al., 2016).

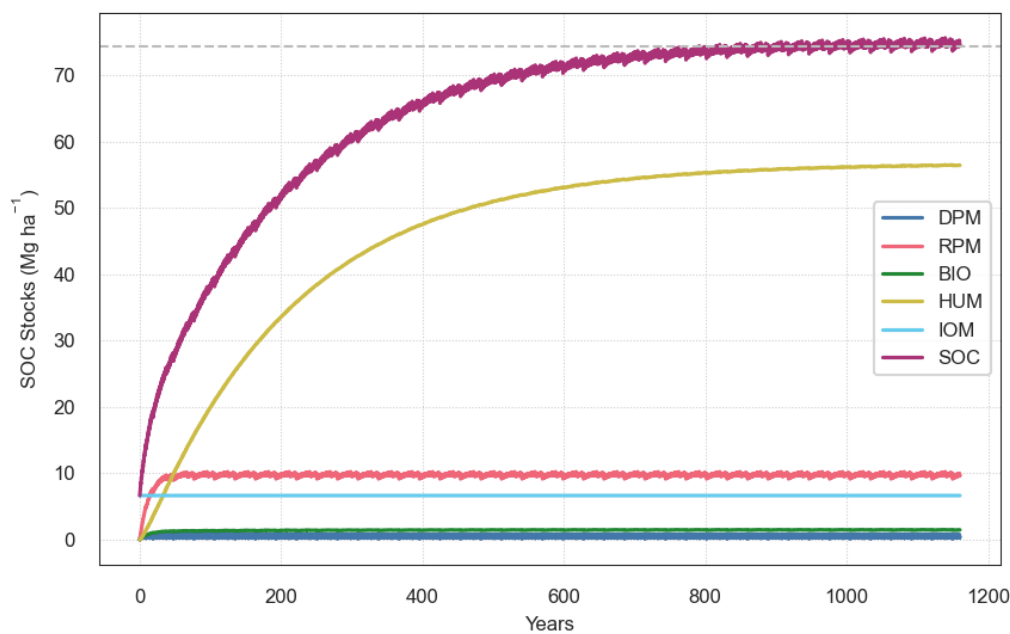


Figure 10: Results of the RothC spin-up period for parametrising soil organic carbon compartments in the Qostanai Region Pilot. The figure displays the dynamics of the four active compartments: Decomposable Plant Material (DPM), Resistant Plant Material (RPM), Microbial Biomass (BIO), and Humified Organic Matter (HUM). The Inert Organic Matter (IOM) compartment, representing clay-associated and decomposition-resistant carbon, remains constant throughout the simulation. Total Soil Organic Carbon (SOC) is the sum of all five compartments. The dashed grey line indicates the observed SOC stocks at the Qostanai Region Pilot.

The SOC stocks in each compartment at t = 1,200 years were subsequently used as initial conditions for predicting future SOC dynamics. Figure 11 presents the SOC stock trajectories under three climate change scenarios (Shared Socioeconomic Pathways, SSPs) and two management options – conventional versus carbon farming – projected to the year 2100. Across all climate scenarios, carbon farming consistently results in higher SOC stocks compared to conventional management. By 2100, SOC stocks under carbon farming are at least 5 Mg ha⁻¹ higher than under conventional practices, regardless of temperature increases.

A notable trend across all scenarios is the initial increase in SOC stocks until mid-century. This suggests that warming initially enhances SOC accumulation, likely due to increased net primary productivity (NPP) and greater plant biomass and root exudates. After 2050, however, this trend diverges by scenario. Under SSP1-2.6, SOC stocks continue to rise, possibly due to moderate temperature increases and slight precipitation gains, allowing carbon inputs to exceed decomposition losses. In the SSP2-4.5 scenario, SOC stocks decline under conventional management post-2050 but plateau under carbon farming. Conversely, under SSP5-8.5, SOC stocks decrease significantly after 2050, returning to initial levels under conventional management by 2100. This decline is attributed to substantially higher decomposition rates driven by hotter and drier conditions.

The model predictions, based on the current parametrization, serve as a decision-support tool, providing preliminary estimates of potential future SOC trends under varying climate and management scenarios. However, the outputs remain highly uncertain, and absolute values should be interpreted with caution. The "carbon farming" parametrization in this study is limited to reduced tillage and permanent soil cover, omitting the full spectrum of regenerative practices. Incorporating additional practices, such as farmyard manure application or cover cropping, would likely amplify the differences in SOC trends between management scenarios. In addition, left crop residues and cover crops change carbon input and the DPM/RPM ratio (Jebari et al., 2021; Coleman & Jenkinson, 1996; Wiltshire & Beckage, 2022) influencing the HUM compartment and total SOC – a factor not yet considered here.

In water-limited regions, such as those projected for northern Kazakhstan under certain climate scenarios, further adjustments to RothC's default parameters may be necessary. For instance, the original moisture modifier in RothC assumes a minimum decomposition rate of 20% (moisture limitation factor for decomposition, $fW = 0.2$), even under severe drought. This overestimates decomposition during dry periods, leading to unrealistic SOC losses in semi-arid environments (Farina et al., 2013). To refine these projections, long-term and reliable datasets on SOC and land management are required for model validation. Without such data, model tuning risks equifinality, making it difficult to attribute predictions confidently to specific parametrizations.

Nonetheless, even with its current simplifications, RothC demonstrates that SOC stocks benefit from carbon farming practices over conventional management in the long term, irrespective of the climate change scenario considered.

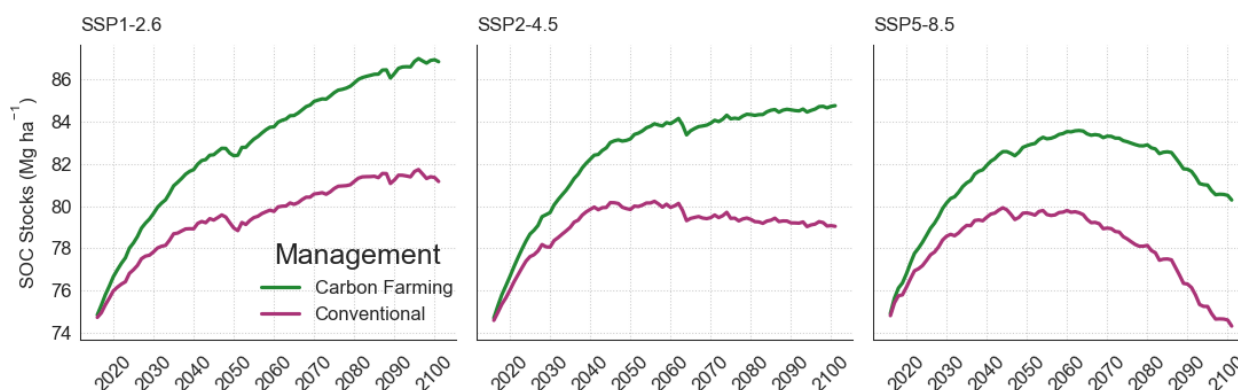


Figure 11: Soil organic carbon (SOC) stock trajectories for the Qostanai Region Pilot, modelled by RothC under three climate projections (Shared Socioeconomic Pathways: SSP1-2.6, SSP2-4.5, and SSP5-8.5) and two management options. The "conventional" management scenario assumes tillage and bare soil conditions outside the vegetation period, while the "carbon farming" scenario incorporates reduced tillage and permanent soil cover throughout the year.

3.3 Greenhouse Gas Mitigation Potential on Farming Level

This section provides a first pilot-based assessment of greenhouse gas mitigation potential at farm level. In contrast to the SOC section above, the emphasis here is on net mitigation pathways rather than on the size of the current soil carbon pool. The analysis therefore considers both carbon stock-related effects and selected non-CO₂ mitigation components, insofar as these can already be linked to observed management changes in the pilot regions.

Given the current stage of the project, the results should be understood as a structured first estimate rather than as a full emissions accounting exercise. Quantitative values are only meaningful where management data and emission-relevant activity data are sufficiently robust. Where this is not yet the case, the report remains transparent and describes the expected mitigation pathway qualitatively.

To evaluate the greenhouse gas mitigation potential of carbon farming relative to conventional agricultural practices, a detailed comparative analysis was conducted focusing on three primary sources of greenhouse gas emissions in agroecosystems: N₂O emissions from nitrogen fertilisers, CO₂ emissions from urea application, and CO₂ emissions from fuel consumption. The results reveal a clear trend of reduced greenhouse gas emissions across all regions when transitioning from conventional to carbon farming practices (Table 3). In Qostanai, the reduction in mineral nitrogen application from 40.0 kg ha⁻¹ to 34.0 kg ha⁻¹, combined with a decrease in urea application from 18.4 kg ha⁻¹ to 15.6 kg ha⁻¹, resulted in a notable decline in N₂O emissions. Similarly, in North Kazakhstan, the reduction in mineral nitrogen from 27.0 kg ha to 23.0 kg ha, with no urea applied, led to a significant decrease in emissions. These patterns were also observed in Akmola and Pavlodar, where reductions in nitrogen inputs translated into lower N₂O emissions.

CO₂ emissions from urea application were also significantly reduced under carbon farming practices. In Qostanai, the reduction in urea application from 40.0 kg ha to 34.0 kg ha⁻¹ avoided 1.2 kg of CO₂ emissions

per hectare. In Pavlodar, the reduction from 10.0 kg ha⁻¹ to 8.5 kg ha⁻¹ avoided 0.2 kg of CO₂ emissions per hectare. In Akmola and North Kazakhstan, where no urea was applied in either system, no additional CO₂ savings were recorded.

Fuel consumption, a major source of carbon dioxide emissions in agriculture, was drastically reduced under carbon farming practices. In Qostanai, fuel use was reduced from 12.0 L ha⁻¹ to 3.0 L ha⁻¹, resulting in a reduction of 24.1 kg of CO₂ emissions per hectare. Similar reductions were observed in North Kazakhstan, Akmola, and Pavlodar, where fuel use was cut significantly, leading to substantial decreases in carbon dioxide emissions.

The total greenhouse gas mitigation potential was calculated by summing the reductions in N₂O, CO₂ from urea, and CO₂ from fuel for each region. The results demonstrate that carbon farming consistently reduces greenhouse gas emissions compared to conventional practices. In Qostanai, the total mitigation potential was 43.3 kg of CO₂e ha⁻¹ year⁻¹. In North Kazakhstan, the total mitigation potential was 29.0 kg CO₂e ha⁻¹ year⁻¹. In Akmola, the total mitigation potential was 42.5 kg CO₂e ha⁻¹ year⁻¹, and in Pavlodar, it was 49.6 kg CO₂e ha⁻¹ year⁻¹. Multiplying these annual mitigation potentials by the agricultural area of each region yields CO₂ emissions reductions of 227,491 Mg year⁻¹ for the Qostanai Region, 127,824 Mg year⁻¹ for the North Kazakhstan Region, 229,115 Mg year⁻¹ for the Akmola Region and 77,820 Mg year⁻¹ for the Pavlodar Region.

These results highlight the significant greenhouse gas mitigation potential of carbon farming in northern Kazakhstan. By reducing nitrogen fertilizer use by 15% and cutting fuel consumption by 75%, carbon farming not only lowers emissions but also enhances soil health, biodiversity, and economic resilience.

Table 3: Greenhouse gas mitigation potential of carbon farming compared to conventional agricultural practices calculated for the four pilots in northern Kazakhstan.

		Conventional				Carbon Farming			
		Qostanai	North Kazakhstan	Akmola	Pavlodar	Qostanai	North Kazakhstan	Akmola	Pavlodar
N ₂ O by fertilisers	Mineral (kg ha ⁻¹)	40.0	27.0	40.0	25.0	34.0	23.0	34.0	21.3
	Urea (46% N) (kg ha ⁻¹)	18.4	0.0	0.0	4.6	15.6	0.0	0.0	3.9
	Total (kg ha ⁻¹)	58.4	27.0	40.0	29.6	49.6	23.0	34.0	25.2
	GHG emissions (kg CO ₂ e ha ⁻¹)	149.5	69.1	102.4	75.8	131.5	60.8	90.1	66.7
CO ₂ from Urea	Urea (kg ha ⁻¹)	40.0	0.0	0.0	10.0	34.0	0.0	0.0	8.5
	GHG emissions (kg CO ₂ e ha ⁻¹)	8.0	0.0	0.0	2.0	6.8	0.0	0.0	1.7
CO ₂ from fuel	Fuel (L ha ⁻¹)	12.0	10.3	15.0	20.0	3.0	2.6	3.8	5.0
	GHG emissions (kg CO ₂ e ha ⁻¹)	32.2	27.6	40.2	53.6	8.0	6.9	10.1	13.4
Total GHG Emissions (kg CO₂e ha⁻¹ year⁻¹)		189.7	96.7	142.6	131.4	146.4	67.7	100.2	81.8
Savings (kg CO₂e ha⁻¹ year⁻¹)						43.3	29.0	42.5	49.6

4 Discussions

4.1 Saturation in SOC Concentrations

Soils have a finite capacity to stabilise organic carbon, whereby additional inputs yield diminishing increases in stable carbon storage. This is commonly referred to as soil carbon saturation. To better characterise this concept, it is essential to distinguish between two functionally distinct carbon fractions: particulate organic carbon (POC) and mineral-associated organic carbon (MAOC). This distinction is critical, as POC is not subject to a strict saturation limit. While it can continue to accumulate with sustained inputs, it remains more susceptible to disturbance. In contrast, MAOC formation depends on the availability of reactive mineral surfaces, which are finite. As a result, MAOC exhibits a saturation behaviour, and the concept of soil carbon saturation primarily refers to the limits of MAOC storage (Georgiou et al., 2025).

Soil carbon saturation can be further described across three levels of storage capacity: theoretical mineral capacity, maximum observed capacity, and effective capacity. The theoretical mineral capacity is determined by the soil's mineral composition and represents the upper bound for MAOC storage, independent of climate or management conditions. As this is primarily a conceptual construct, it remains unclear whether this limit has been reached in natural systems, given the difficulty of quantifying it. The maximum observed capacity refers to the highest levels of MAOC storage detected under a range of environmental and management conditions, providing an empirical benchmark. The effective capacity refers to the storage limit under specific climate and management regimes. Under such conditions, MAOC accumulation may plateau well below the theoretical mineral capacity due to environmental constraints (Georgiou et al., 2025).

Empirical evidence suggests that most managed soils are currently far from their MAOC saturation capacity, indicating a substantial potential for additional carbon storage. However, quantifying absolute saturation limits remains challenging and a topic of open research, as theoretical capacities are difficult to measure and observed soil carbon dynamics often do not clearly exhibit saturation behaviour. Furthermore, the time horizon over which saturation may be approached is likely to be long. Soil carbon stocks typically respond to changes in management over multi-decadal timescales, reflecting both the gradual formation of MAOC and the fact that many soils remain well below their potential storage capacity (Georgiou et al., 2025).

Against this background, observed SOC levels at the experimental sites provide a basis for assessing their approximate position relative to saturation under natural reference conditions. The sites in Qostanai, North Kazakhstan and Akmola are located on Chernozem soils, while the site in Pavlodar is situated on Kastanozems. Chernozems are characterised by naturally high SOC contents, typically in the range of 5-6% under undisturbed conditions. However, long-term agricultural use has led to substantial carbon losses, with reported reductions of up to 11% resulting in current SOC levels of approximately 4.5-5%. The SOC levels observed at the study sites are considerably lower, indicating strongly degraded conditions typical of areas under continuous cultivation and monocropping, where reductions of up to 30% have been reported

(Zharlygassov et al., 2025). In contrast, Kastanozems exhibit considerably lower natural SOC levels, generally ranging from 1.5-2.5% in the topsoil (Kabala et al., 2025). This is reflected in the measured SOC contents of the Pavlodar site and corresponds to both drier climatic conditions and lower inherent carbon storage capacity. Taken together, the observed SOC levels indicate that the study sites are far from their potential MAOC saturation capacity. Saturation is therefore unlikely to be approached within short- to medium-term time horizons and substantial capacity for additional carbon storage remains. Against the background of the pilot results, this means that the currently observed SOC levels should not be interpreted as evidence of near-term saturation. Rather, the measured values suggest that the experimental sites still retain room for additional carbon storage under sustained and site-appropriate management.

4.2 Measurement-Reporting-Verification and Related Risks

The MRV-related risks discussed in this report should be understood in the context of an early pilot phase. The purpose of the present assessment is not to demonstrate that the four pilot regions are already ready for immediate credit issuance, but to show how core MRV questions become visible under real field conditions. In this respect, the pilot work provides important methodological learning on baselines, sampling consistency, uncertainty, and the practical interpretation of early changes in SOC and mitigation-related variables.

A first key issue is additionality. Any future claim that carbon farming in the pilot regions leads to verified removals or emission reductions must be assessed against a credible business-as-usual baseline. This means that the observed effect should not simply reflect standard practice, regulatory obligation, or a trend that would likely have occurred without the project-related intervention (Paul et al., 2023). At the current stage, the report can identify likely additionality pathways, but it cannot yet confirm them with the same level of certainty that would be required for formal crediting.

A second issue is permanence. Soil carbon gains are not automatically permanent, especially under dryland conditions and changing management. Drought, future tillage, erosion, fire, or the discontinuation of improved practices may all reduce or reverse previous gains (Paul et al., 2023). For this reason, any future registry-related use of pilot results would require conservative accounting, multi-year maintenance commitments, and a clear treatment of reversal risk. This is particularly relevant in Kazakhstan's climate context, where inter-annual variability is high and long-term soil-carbon stability cannot be assumed.

A third issue is leakage, which refers to the relocation of emissions to other regions (Paul et al., 2023). Although leakage risks are often more visible in larger programme settings than in single pilot plots, the possibility still needs to be considered. Emission reductions or carbon gains in one field should not be interpreted as a net benefit if they are offset by more intensive input use, stronger tillage, or displaced emissions elsewhere in the farming system. At the pilot stage, leakage is best addressed through transparent documentation of field-level practices and a cautious interpretation of net effects.

Finally, uncertainty and quality assurance are central to the credibility of the results. In the present report, uncertainty arises from sampling variability, spatial heterogeneity, laboratory error, short monitoring duration, incomplete activity data for some non-CO₂ components and uncertainties in bulk density

estimates. The latter represents one of the more influential sources of uncertainty at field scale (Goidts et al., 2009). Bulk density was derived using the SoilGrids dataset, a global product compiled from national contributions. In the case of Kazakhstan, ground-based reference data are relatively scarce, resulting in comparatively high uncertainties in the underlying variables (Poggio et al., 2021). These uncertainties propagate through the calculation process, and the resulting SOC stock estimates should therefore be interpreted conservatively. These uncertainties underline the need for robust quality assurance procedures. In this context, quality assurance should be based on transparent field protocols, consistent depth intervals, laboratory reference analysis, plausibility checks, and a clear distinction between measured values and model-based estimates. In future stages, these pilot experiences can serve as an important foundation for a broader national MRV platform with accredited QA/QC routines, confidence intervals, and registry-compatible reporting. In practical terms, the pilot results presented in this report should therefore be treated as a methodological baseline for further monitoring, not as final registry-ready figures.

5 Key Findings: Unlocking Potential, Scaling Solutions, and Policy Pathways

5.1 Policy Framework

This section briefly situates the pilot results within Kazakhstan’s wider policy and institutional context. It does not aim to repeat the national framework in full, as this has already been discussed in the Background & Technical Paper (Çeltikoğlu et al., 2025). The focus in this section is therefore on institutional relevance and policy linkage, not on repeating the full argument of the companion papers.

Carbon farming is not yet explicitly defined or operationalised within Kazakhstan’s regulatory framework and no dedicated legal or policy instrument currently directly governs soil carbon sequestration activities. However, Kazakhstan has developed a comprehensive climate policy framework, with the 2060 Strategy, the Nationally Determined Contribution (NDC) and the Environmental Code providing the legal and strategic basis for climate action, including the national Emissions Trading System (ETS) and carbon registry. Kazakhstan’s Strategy for Achieving Carbon Neutrality by 2060 (2023) and the NDC define agriculture, water management, and forestry as priority sectors for emission reduction and adaptation. The Environmental (Ecological) Code (2021, amended 2023) provides the legal basis for climate policy, including the national ETS and the establishment of a national carbon registry. An overview over key national policies is provided in Table 4.

Kazakhstan launched Central Asia’s first national ETS in 2013. Approximately 200 entities in power and heavy industry participate, covering about 50% of national emissions. Current ETS coverage focuses on large stationary emitters in energy and industry; agriculture and land use remain outside the compliance scope. After a temporary suspension in 2016-2017 for reforms, the ETS restarted in 2018 with strengthened MRV standards. Agriculture and waste remain outside the ETS scope, but offset mechanisms can provide indirect integration. However, the current ETS design, based on free allocation and low price signals, provides only limited incentives for emission reduction and low-carbon investment.

To align with the 2060 target and address current design limitations, the government is preparing a comprehensive reform of its architecture, including partial auctioning, digital registry integration and improved monitoring systems, expected to take effect by 2026. As of 2024, efforts are underway to digitise emissions reporting across sectors and automate allowance tracking. Post-2025, there are plans to partially auction allowances to deepen the market (legislative changes are on the parliamentary agenda). For sectors outside the ETS, voluntary markets and offset credits are key flexibility instruments. Under the current Environmental Code, ETS-covered companies may use nationally approved offset credits toward compliance – a pathway through which agricultural soil-carbon projects could be formally recognized and monetized within the ETS; however, we strongly recommend that any use for compliance should not occur before 2030 and only after a formal integrity review confirms additionality, permanence, and robust MRV (more in depth information on this matter can be found in the Policy Brief and Background & Technical Paper). Article 298 defines “carbon credits” as verified reductions or removals, with credits recorded in a national registry. As of 2025, Paris Agreement Article 6 rules are being finalized, providing a timely window to embed agricultural carbon projects into both domestic and international markets.

Institutionally, climate and agricultural policy implementation in Kazakhstan is shared among several bodies. The Department of Climate Policy and Green Technologies under the Ministry of Ecology and Natural Resources (MENR) coordinates national climate strategies and greenhouse-gas inventory processes. The Joint-Stock Company Zhasyl Damu (JSC Zhasyl Damu) – a state-owned enterprise supervised by the MENR – manages the national carbon registry and operates the Emissions Trading System (ETS), including allowance allocation and tracking, as mandated by the Environmental Code (2021). The Ministry of Agriculture is responsible for land management, agricultural support, and extension services. The Ministry of National Economy and Ministry of Finance shapes subsidy policies and carbon finance. The Astana International Financial Centre (AIFC) has recently emerged with sustainable finance initiatives and trading infrastructure for carbon credits. Yet, a comprehensive coordination mechanism is still lacking, responsibilities for climate change and sustainable land management remain fragmented across institutions, and there is no dedicated unit to steer carbon farming specifically.

This fragmentation challenges the implementation of high-level strategies. For example, while the 2060 Strategy endorses carbon farming, concrete programs bridging agricultural and environmental policy to deliver farm-level adoption are still missing. Local governments have adaptation plans but lack mandates, resources, and capacities as well as the MRV infrastructure to implement and monitor carbon farming initiatives. Addressing these weaknesses requires a cross-ministerial climate and agriculture working group and targeted capacity building for local administrations. At the same time, existing instruments are not idle: the Environmental Code recognizes project-based credits and sets a market framework; the Land Code and Organic Production Law emphasize soil health. The task now is to close the gap between strategy and farm-level action, and to start turning the carbon-farming vision into incentives and guidance that farmers can adopt.

Table 4: Key National Policies for Carbon Farming in Kazakhstan

Policy/Strategy	In Force	Relevance and Impact on Carbon Farming
Strategy for Achieving Carbon Neutrality 2060	2023	Identifies climate-smart agriculture as a priority; targets scaling carbon farming. Foresees agriculture/land as net carbon sinks by 2060. Provides high-level political backing.
Nationally Determined Contribution (NDC)	2021	Pledges a 15% emissions reduction by 2030. Names agriculture, water, forestry as priority sectors.
Environmental (Ecological) Code	2021	Provides legal basis for the national ETS; defines carbon credits/offsets. Recognizes project-based credits and records them in the national registry.
Green Economy Concept	2013	Long-term sustainability vision. Focus on water/energy for 2020–2030; plans sustainable land use for 2030–2050. The latter is a window to embed carbon farming into national strategy.
Land Code & Organic Production Law	2003/2015	Land Code promotes sustainable soil use and prohibits degradation; Organic Production Law aims to preserve soil fertility. Not carbon-specific but indirectly encourage practices that increase soil organic matter (crop rotations, organic amendments).
Qazaq Green Carbon Certification Program	2023	New national voluntary carbon standard. Aims to enable registration and trade of credits aligned with international integrity. Agricultural/land projects could be certified domestically. Not yet integrated with ETS but creates a national framework for carbon farming certification.

5.2 Market Integration

This section focuses on the economic and registry-related implications of the pilot results. Legal and institutional background is only referred to where it directly affects market access, certificate design, or the use of contribution claims.

5.2.1 ETS integration

Kazakhstan’s carbon market landscape is shaped by two main components: the ETS and emerging voluntary carbon markets (VCM). VCMs complement the ETS by providing additional pathways for climate finance. As the central compliance-based instrument, the ETS defines the current structure and price signals of

Kazakhstan's carbon market. Under the ETS, installations must comply with emission caps: those below their allocation can sell surplus allowances, while those exceeding must purchase additional ones. To date, all allowances have been allocated free of charge, keeping the carbon price extremely low around USD 1 per t CO₂eq. Comparative analyses by the World Bank (2023) and the OECD (2023) indicate that carbon prices below USD 15–25 per t CO₂eq provide only limited incentives for emission reductions, whereas prices within or above this range begin to influence investment behaviour towards low-carbon technologies. In this context, Kazakhstan's current price level is insufficient to drive low-carbon investment or stimulate meaningful abatement. Without expanding coverage and improving market design, the ETS risks remaining in a low-price, low-liquidity equilibrium. In response to these limitations, Kazakhstan is pursuing both the reform of the ETS and the parallel development of voluntary carbon markets.

Within this context, Kazakhstan launched the Qazaq Green Voluntary Carbon Certification Program (2023) and is developing a national offset and trading infrastructure within the Astana International Financial Centre to promote voluntary credits. Together, these initiatives aim to improve domestic credit quality, transparency, and investor confidence while ensuring consistency with international integrity standards (ICVCM, VCM, ISO 14064). The goal is to enable domestically developed projects targeting forestry, rangeland, or agriculture to issue credits recognized in overseas voluntary markets. AIFC plays a central role in operating registries and attracting foreign investors.

In parallel to these institutional developments, grassroots initiatives have emerged on the voluntary carbon markets (VCM). The Qazaq Carbon platform (2023) began projects in regions like the Aral Sea basin, focusing on afforestation and land restoration. Working with international standards such as Plan Vivo and Open Forest Protocol, the platform aims to enable small landholders to generate credits.

The interaction between the ETS and the VCM can help mobilise climate finance for agriculture. However, carbon-farming credits from soils or biomass should not be used to offset emissions from other sectors. Given uncertainties about permanence – such as potential reversals caused by drought, fire, or changes in management – and the challenge of proving additionality, these credits are unsuitable as compliance substitutes for energy, industry, or transport. Doing so would undermine the overall net-zero trajectory.

A more robust approach is to use voluntary-market demand to fund results-based payments or “contribution claims”, meaning credits that are issued and immediately retired without being used for compliance. In this model, finance flows to farmers as performance-based rewards for verified emission-reduction or carbon-sequestration practices under a transparent MRV framework. Any future link between agriculture and the ETS must therefore remain strictly non-substitutive – applying the mitigation-first principle, prohibiting cross-sector offsetting, and ensuring transparent registry treatment to avoid double counting. This design would allow agriculture to access private climate finance while preserving environmental integrity.

Limited trading, underdeveloped digital infrastructure, shortages of skilled personnel, and inconsistent reporting methodologies continue to hinder ETS performance. Addressing these structural gaps is a precondition for strengthening the ETS and enabling the future inclusion of new sectors such as agriculture. In short: Kazakhstan's carbon markets are nascent but poised for rapid evolution. Strengthening ETS scope

and pricing, developing a transparent, credible voluntary market, and integrating agricultural carbon projects can create the economic incentives needed for carbon farming.

5.2.2 Pathways for Translating SOC Gains into Marketable Certificates

At present, the most credible pathway for translating soil organic carbon gains into marketable outcomes in Kazakhstan lies not in immediate use within the compliance segment of the ETS, but in high-integrity voluntary-market arrangements and other results-based payment models. In practical terms, SOC gains would first need to be quantified as verified net removals relative to a conservative baseline and then recorded in a transparent registry as project-based units with unique serial numbers. In line with the broader logic of this report, such units should be treated primarily as a channel for mobilising climate finance into agriculture rather than as a substitute for emission reductions in energy, industry, or transport. A cautious approach is therefore warranted: any future linkage to the ETS should remain non-substitutive and should only be considered once robust methodologies, registry interfaces, and integrity safeguards have been demonstrated in practice.

For SOC gains to be certifiable, the measurement, reporting and verification framework must be sufficiently robust to distinguish genuine management effects from natural variability and short-term fluctuations. A layered MRV architecture is required, combining farm records, stratified soil sampling, accredited laboratory analysis, remote sensing, and process-based modelling. Within such a system, credits or payment-relevant units should be issued only for conservatively estimated gains, with quantified uncertainty deducted from reported results and with additionality tested against business-as-usual baselines as well as regulatory, common-practice, and financial screens. Permanence remains a central constraint, particularly under Kazakhstan's drought-prone and climate-variable conditions; accordingly, buffer reserves, multi-year maintenance commitments, ex ante and ex post monitoring, and reversal procedures are necessary. Leakage must also be checked to ensure that carbon gains or emission reductions in one parcel are not offset by intensified emissions elsewhere. Where biochar is included, it requires a separate accounting logic based on material quality disclosure, mass-balance documentation, and conservative permanence factors.

If these conditions are met, economic benefits may arise through several, partly complementary channels. Farmers could receive supplementary income through verified voluntary credits, contribution claims with immediate retirement, public or private result-based payments, or hybrid schemes that combine practice support with performance bonuses. Beyond certificate income, the farm-level business case is likely to depend just as much on co-benefits: lower fuel and labour requirements under reduced tillage systems, improved nutrient efficiency, better water retention, more stable yields, and in some cases diversified revenues from agroforestry or differentiated market access. At the same time, the Kazakhstan context imposes clear limitations. Low ETS price signals, underdeveloped digital infrastructure, shortages of skilled personnel, fragmented institutional responsibilities, and high MRV and transaction costs may significantly constrain early monetisation. The focus-group evidence also suggests that farmers will only engage at scale where a credible business model, local demonstration effects, and organised support infrastructure reduce the perceived risk of transition (Çeltikoğlu et al., 2025). For this reason, phased implementation, project aggregation, and transparent coordination between AIFC, JSC Zhasyl Damu, agricultural authorities, and project developers appear to be key enabling conditions for any viable market integration of SOC gains.

This pilot evidence suggests that market integration should be approached in a phased and conservative manner. In the near term, the most credible pathway lies in contribution-based claims or other results-based finance models, rather than in immediate compliance use. This means that any units linked to agricultural carbon gains should, during an initial phase, primarily serve to mobilise climate finance and should be immediately retired rather than used to offset emissions in other sectors. A possible future interface with the ETS would therefore depend on demonstrated integrity, including robust additionality, permanence safeguards, quantified uncertainty, and transparent registry treatment.

5.3 Scaling Possibilities

Scaling should build on the lessons generated by the pilot regions rather than bypass them. In this sense, the four pilot sites are not only test fields for individual practices, but also learning environments for monitoring design, data integration, and implementation logic. A credible scaling pathway would therefore require gradual expansion through standardised methods, clear eligibility criteria, and a governance structure capable of linking field evidence, advisory services, and financial incentives.

From this perspective, standardisation is not only a technical issue but also a scaling condition. Harmonised sampling logic, comparable reporting formats, transparent QA/QC, and conservative accounting rules would make it easier to translate pilot experience into larger regional programmes. The practical value of the pilot phase thus lies not only in the measured results themselves, but also in the development of operational templates that can later support regional expansion under Kazakhstan's agro-ecological diversity. For this reason, scaling should proceed only once the pilot regions have generated sufficiently comparable evidence on sampling, reporting, and implementation logic (additional detail on the proposed pilot-to-scale approach and its technical, economic, and institutional preconditions is set out in the Background & Technical Paper).

In this context, the German DIN SPEC 3609 could serve as a reference model by establishing harmonised rules for the quantification and valuation of soil organic carbon. The standard aims to align diverse existing private-sector initiatives under a common methodological framework, thereby ensuring comparability, transparency, and credibility of project outcomes. The DIN SPEC 3609 (2024) outlines a robust MRV framework, which defines requirements for standardised soil sampling and laboratory analysis as well as independent third-party verification. Moreover, it defines conservative accounting approaches to address uncertainty and reversal risks and emphasises digitalisation as a prerequisite for scaling. While developed in a German context, these principles can serve as a reference for scaling carbon farming in Kazakhstan and guide the development of a national MRV platform in alignment with international standards.

Beyond technical standardisation, scaling also depends on the design of incentive structures that can support adoption at farm level while ensuring environmental integrity. In this context, three broad categories of instruments can be distinguished, namely action-based, result-based, and hybrid approaches, each associated with distinct strengths, risks, and MRV requirements. Action-based instruments, which provide payments for the adoption of defined practices, offer lower transaction costs and simpler implementation but entail greater uncertainty regarding climate outcomes. In contrast, result-based mechanisms link payments to verified mitigation outcomes and thus provide higher environmental integrity, albeit at the cost of more demanding MRV systems and increased exposure of farmers to performance and

price-related risks. Hybrid models combine elements of both approaches by pairing low-risk, practice-based payments with performance-linked bonuses, thereby reducing entry barriers while maintaining incentives for measurable outcomes.

In the case of Kazakhstan, scaling could furthermore build on a combination of instruments already reflected in existing policy discussions, including the re-targeting of agricultural support towards practices aimed at enhancing soil carbon, the use of result-based public programmes or carbon funds to purchase verified mitigation outcomes under conservative baselines and buffer requirements, and the aggregation of farms to enable participation in verification and carbon-market transactions. Hybrid approaches, combining practice-based payments with performance-based bonuses, are particularly relevant in early stages, as they lower adoption risks while maintaining a link to verified outcomes.

Taken together, scaling carbon farming requires a coherent combination of standardised methodologies, robust MRV systems, and well-designed incentive structures. Pilot regions play a critical role in generating the evidence and operational experience needed to underpin this transition. Ensuring that scaling is grounded in comparable data, credible verification, and economically viable delivery models will be essential for moving from pilot initiatives to a functioning and trustworthy carbon farming framework in Kazakhstan.

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