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SOILS AS A KEY TO CLIMATE RESILIENCE: INTERNATIONAL EXPERIENCE AND A ROADMAP FOR DEVELOPING UZBEKISTAN'S CARBON INFRASTRUCTURE

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Annotation: Soil is a key manageable carbon reservoir and the foundation of climate-resilient agriculture, especially in arid regions. This article synthesizes international and Russian experience with carbon monitoring sites and soil-based carbon dioxide removal (CDR) technologies (biochar, cover crops, conservation agriculture). Using Uzbekistan as a case study. The article analyzes climate risks and soil degradation, and proposes a step-by-step roadmap for developing a national carbon(C) infrastructure, including a network of monitoring sites, a measurement reporting and verification (MRV) system, and mechanisms for certifying C credits for the country's agricultural landscapes

Key words: soil carbon, carbon monitoring sites, biochar, CDR projects, soil re-carbonization, climate-resilient agriculture, Uzbekistan, nature-based solutions.

Annotatsiya: Tuproqlar arid hududlarda boshqariladigan asosiy uglerod rezervuari va iqlimga chidamli qishloq xo'jaligining tayanchi sifatida ko'riladi. Maqolada Rossiya va boshqa mamlakatlarda karbon poligonlari hamda biochar, qoplovchi ekinlar va konservatsion dehqonchilikka asoslangan tuproq CDR amaliyotlari tajribasi umumlashtiriladi. O'zbekiston misolida iqlimiy xatarlar va tuproq degradatsiyasi tahlil qilinib, karbon infratuzilmasini rivojlantirish bo'yicha bosqichma-bosqich milliy "yo'l xaritasi" taklif etiladi: poligonlar tarmog'i, MRV tizimi va uglerod birliklarini sertifikatlash.

Kalit so'zlar: tuproq uglerodi, karbon polygonlari, biochar, CDR loyihalari, tuproqni rekarbonizatsiya qilish, iqlimga chidamli qishloq xo'jaligi, O'zbekiston, tabiatga asoslangan yechimlar.

Аннотация: Почвы рассматриваются как ключевой управляемый резервуар углерода и основу климатически устойчивого земледелия в аридных регионах. В статье обобщён международный и российский опыт карбоновых полигонов и почвенных CDR-технологий (биоуголь, покровные культуры, консервационное земледелие). На примере Узбекистана

проанализированы климатические риски и деградация почв, предложена поэтапная «дорожная карта» национальной карбоновой инфраструктуры, включающая сеть полигонов, MRV-систему и механизмы сертификации углеродных единиц для агроландшафтов страны.
Ключевые слова: почвенный углерод, карбоновые полигоны, биоуголь, CDR-проекты, рекарбонизация почв, климатически устойчивое земледелие, Узбекистан, природно-ориентированные решения.

1. INTRODUCTION

Global climate change is one of the key threats to sustainable development. An increase in frequency and intensity of extreme weather events, shifts in hydrological regimes, and declining productivity of agro-ecosystems are already widely observed in many regions of the world. To achieve the goals of the Paris Agreement and limit global warming to 1.5–2°C, reducing emission of greenhouse gas (GHG) alone may not be adequate. Rather, a systemic transition towards nature-based solutions is essential. The latter must harness the carbon (C) sink capacity of ecosystems and based on the strategy of the recarbonization of the terrestrial biosphere [7, 13, 18].

According to the policy brief by the United Nations Development Program (UNDP) and the Government of Uzbekistan, Green Growth and Climate Change in Uzbekistan [36], the development of a green economy and the large-scale deployment of nature-based technologies are identified as priorities of the national climate policy. Towards global implementation, however, policy-makers must address these objectives by creating national C removal portfolios comprising of the balanced sets of natural and technological solutions adapted to the socio-economic conditions of specific countries [9]. For Uzbekistan, where arid ecosystems and irrigated agriculture predominate, a pertinent strategy is to combine soil-based carbon dioxide removal (CDR) technologies (biochar, cover crops, soil recarbonization) with institutional mechanisms for measurement, reporting and verification (MRV). This strategy is reinforced by the development of the Uzbekistan Green Taxonomy, in which the classification of "green" projects is considered a basic tool for attracting investment in approaches of the low-C development [38].

Soils occupy a central place in such a strategy, representing the largest terrestrial C reservoir (≈ 2400 Gt C to 1-m depth), which significantly exceeds the C stock of the atmosphere and biosphere combined [25, 27]. Thus, even moderate changes in soil organic carbon (SOC) stocks can substantially influence the global C budget [19]. Therefore, the conservation and restoration of SOC is one of the most reliable and scalable mechanisms of atmospheric CDR and long-term stabilization in soil organic matter (SOM). In the international agenda, these approaches are being advanced within the framework of nature-based solutions and the "4 per 1000" initiative, according to which an annual SOC increase of about 0.4% in the top 0 to 40 cm depth could potentially offset a significant share of anthropogenic emissions [23, 25].

In many countries—from Europe and North America to Australia and the states of the Global South—networks of observational and C monitoring sites are being established to assess the C cycle. Using eddy covariance, chamber-based measurements, and C stock inventories, these sites provide baseline emission levels and assess the effectiveness of nature-based technologies in agricultural landscapes [7, 27, 32]. Such systems are becoming the core of national C infrastructure, supplying comparable data for modelling, MRV platforms, and climate projects (Fig. 1). Russia is actively developing its own network of C monitoring sites and legal mechanisms to support them, and is integrating these efforts into the international architecture of climate monitoring and regulation [1, 12, 22].

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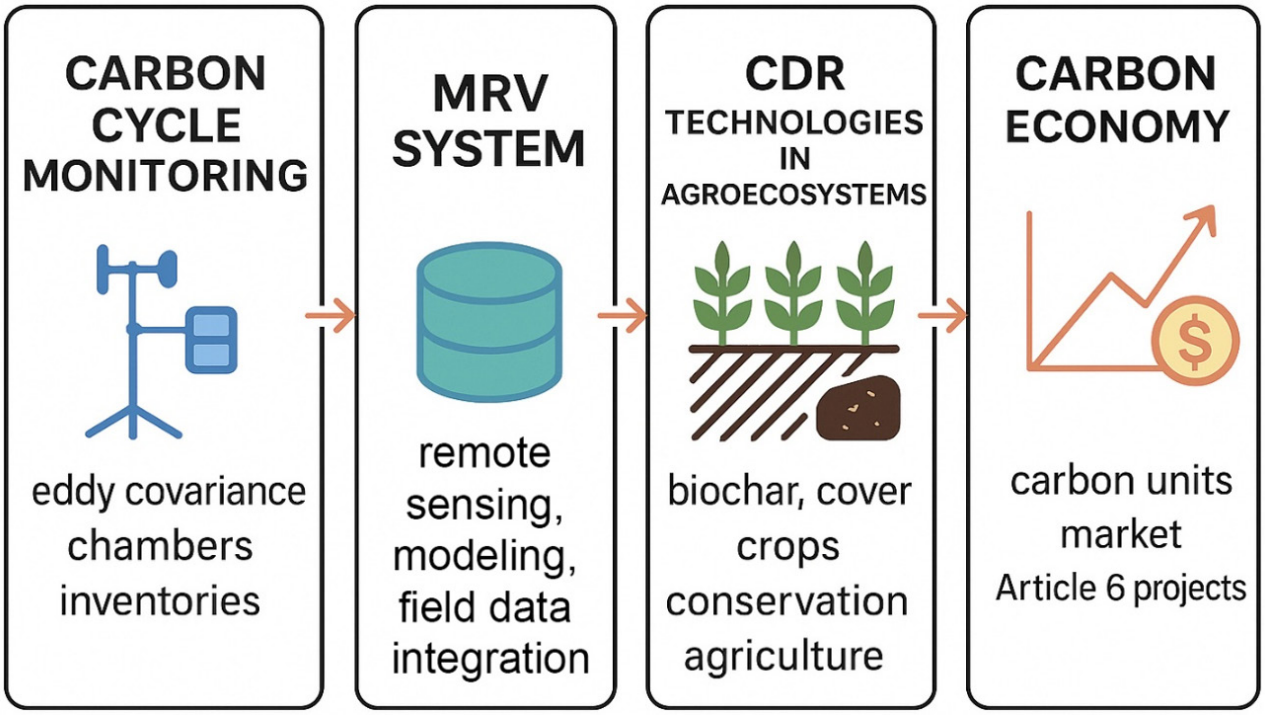


Figure 1. Carbon management system: from monitoring to the economy (monitoring → MRV → CDR technologies → carbon market).

The strategy presented in this article is particularly relevant for the countries of Central Asia, where an arid climate, soil degradation, and low SOM content aggravate the vulnerability of agricultural landscapes to anthropogenic climate change (ACC). Uzbekistan, combining a high share of irrigated agriculture with rich agrarian traditions and increasing climate risks, represents an appropriate environment for adapting soil-based CDR technologies that have already been tested in arid and semi-arid regions worldwide, and towards an endeavor for establishing sites for its own system of monitoring.

This review article encompasses an analytical approach. Its primary objectives comprise: 1) evaluate the role of soil ecosystems in ensuring climate resilience and low-C economic development, 2) synthesize international and Russian experience in monitoring C cycle, 3) discuss a strategy of implementation of soil-based CDR projects, and 4) analyze the potential and prospects for adapting these approaches under the agro-ecological conditions of Uzbekistan.

2. EVALUATING THE CARBON CYCLE AND ITS ROLE IN CARBON MONITORING SITES

Quantitative assessment of GHG fluxes between the atmosphere and the land surfaces is the foundation of modern climate science and a necessary condition for developing realistic low-C economy [7, 27]. The objective of such monitoring is not only to quantify the current emission of GHGs but also to generate stable time series that capture the spatial, seasonal, and interannual variability of C exchange across different ecosystem types, including agricultural landscapes [20, 32]. These data form baseline emission levels that serve as a reference for evaluating the climate impact of nature-based technologies and CDR projects.

In many countries of Europe, North America, and Australia, monitoring is organized in the form of networks of field stations and C monitoring sites (Fig. 2), designed for assessing the C cycle and testing soil-based measures aimed at C sequestration [12, 13]. Such sites are integrated into international observation systems and form the core of national C

infrastructure, providing comparable data for models, MRV platforms, and climate projects [4, 32].

The methodological framework of C monitoring sites typically includes three complementary groups of methods:

· **Eddy covariance:** It is a direct measurement method of vertical fluxes of CO2, H2O and other gases between the surface and the atmosphere, enables the acquisition of data on the diurnal and seasonal dynamics of C exchange at the ecosystem level [3].

· **Chamber-based methods:** It measure instantaneous CO2, CH4 and N2O emissions using static or dynamic chambers combined with portable infrared gas analyzers. These approaches provide high spatial resolution and make it possible to assess the effects of specific agricultural practices [3, 27].

· **Inventory-based approaches:** These are designed to assess organic and inorganic C stocks and N2O in different soil horizons and land-use types, and provide the basis for estimating long-term SOC changes and testing different models [27].

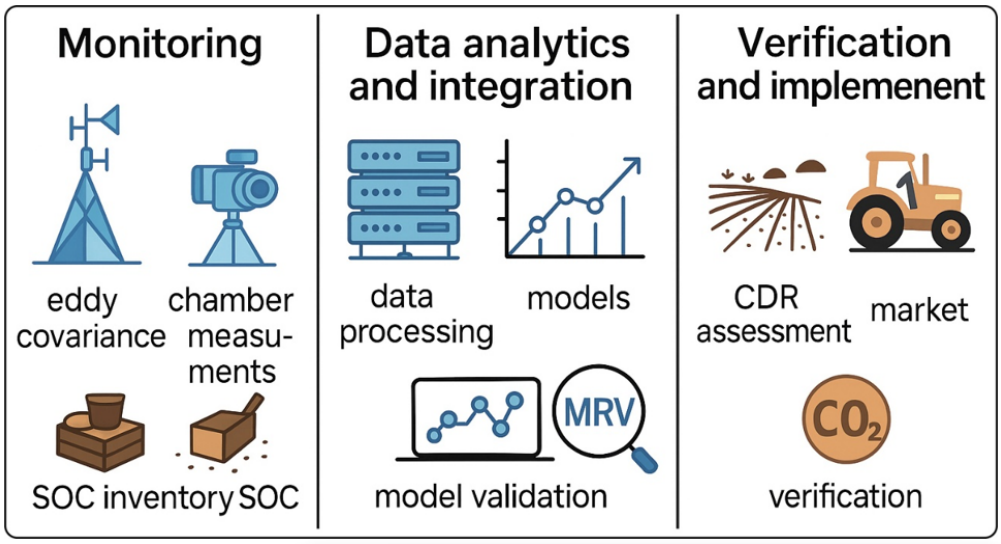


Figure 2. Structure of a carbon monitoring site and its key functions (monitoring, data analytics and integration, verification, and implementation of CDR projects).

The combination of micrometeorological, chamber-based, and inventory measurements provides an integrated understanding of the C balance and enables comparison of the effects of different CDR technologies. At the same time, data from monitoring sites are used not only for scientific analysis but also as an evidence base for the certification of climate projects, because they establish reliable baseline levels and observation datasets for MRV systems [4, 32].

The development of digital and remote-sensing technologies is taking C monitoring to a new level. New MRV platforms, such as the European Field Observatory Network (FiON), demonstrate the potential of integrating satellite data, in situ sensors, and model-based assessments to support operational accounting of soil C and GHG fluxes over large areas [26]. Similar approaches are gradually being introduced in Russia. An example of this approach is the Kuchak C monitoring site of Tyumen State University. This site comprises of chamber measurements, micrometeorological observations, and C stock inventories which are combined across forest, wetland, and agricultural landscapes.

Taken all together, C monitoring sites perform three key functions. First, a monitoring function: to provide continuous measurements of GHG fluxes and meteorological parameters required to analyze the seasonal and

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interannual dynamics of C exchange. Second, an analytical function: to serve as a basis for modelling C balances and producing maps of emission indicators, which is critical for planning climate and agricultural policy [23]. Third, a verification function: to generate datasets used to verify reporting and certify climate projects within MRV systems at national and international levels [42].

For Uzbekistan, the experience of establishing C monitoring sites in arid and semi-arid regions of the world is of particular interest. It shows how standardized measurement protocols and long-term observations allow a transition from isolated experiments to a stable soil C management system that simultaneously supports scientific research, agricultural practices, and C market instruments. In the following sections, this experience is considered as a methodological prototype for designing the first C monitoring site and configuring an MRV system in the agricultural landscapes of Uzbekistan.

3. CDR PROJECTS AS THE PRACTICAL PHASE OF THE CARBON AGENDA

Monitoring the C cycle and the establishing baseline levels create the scientific foundation for emission assessment but do not, by themselves, ensure the achievement of climate neutrality. The next step is a transition from observation to active technologies of C removal and long-term sequestration. In this context, CDR solutions— methods for extracting CO2 from the atmosphere followed by its stabilization in biogeochemical or engineered reservoirs— are of particular importance [7, 17]. A substantial share of these approaches is directly related to the management of plant biomass and SOM stock of agricultural landscapes [13, 27].

Modern CDR technologies are classified into three groups [7]. The first includes biological methods (i.e., reforestation, agroforestry, wetland and vegetation restoration) through which C is stored in biomass and soil for decades to centuries. The second group encompasses soil-based measures such as under cover crops, mulching, incorporation of organic residues, reduced tillage, and other elements of conservation agriculture (CA) that promote increases in SOC stocks [23, 29]. The third group consists of geochemical approaches, such as enhanced weathering of silicate rocks and mineral carbonation, which provide long-term CO2 sequestration in the form of stable minerals [5].

In practice, CDR solutions are increasingly being integrated into agricultural landscapes through pilot projects and portfolios of technologies. For example, large-scale enhanced weathering experiments in the United States have demonstrated the potential to combine long-term C sequestration with increases in crop yields [6]. In EU countries, methodologies for certifying agricultural CDR credits are being developed, taking into account both biological and geochemical approaches [1, 10]. These examples illustrate the transition from an experimental phase toward incorporating CDR into full-scale climate and economic policy.

Particular attention among soil-based technologies is given to biochar, a product of biomass pyrolysis under limited oxygen supply. Its high degree of aromaticity, well-developed porosity, and chemical stability simultaneously improve the agrophysical properties of soils and create a long-term C reservoir [31, 41]. As a result, biochar is considered one of the most technologically advanced and scalable soil-based CDR technologies.

Meta-analyses of field and modelling studies show that biochar application on average:

- increases SOC content by 20–30% [14];
- reduces N2O emissions by 20–50% [8,

31];

· enhances water-holding capacity, field capacity, and porosity by 10–30% depending on soil type [11]; and

· increases crop yields in field experiments by 10–20% under optimal application rates and pyrolysis conditions [39].

At the same time, the effect of biochar differs depending on soil texture, climate, antecedent SOC levels, feedstock type, and pyrolysis temperature regime [41]. In some cases, impacts on yields and GHG emissions are neutral, and economic efficiency depends on biomass availability as well as on the costs of pyrolysis and logistics. Therefore, the use of biochar requires regionally adapted approaches and careful assessment of benefits and costs.

The most promising results are achieved when biochar is combined with cover crops and other pillars of CA. In such systems, part of the C accumulates temporarily in biomass, while another part becomes stabilized as slowly decomposing soil C, and creating agro-ecosystems with a positive or near-neutral C balance [23, 25, 29].

For arid and semi-arid regions, including the countries of Central Asia, the combination of biochar, cover crops, and resource-efficient tillage offers a dual benefit: it simultaneously increases SOC stock and enhances the resilience of agro-ecosystems to drought, salinity, and structural degradation. Thus, soil-based CDR technologies are viewed as a key component of future pilot projects and carbon monitoring sites in Uzbekistan (Fig. 3).

4. SOIL CARBON IN UZBEKISTAN: RISKS, STATUS, AND POLICY CONTEXT

4.1. Climate risks and water stress

Uzbekistan is among the most climate-vulnerable countries of Eurasia. According to World Bank assessments, over the past decades the country's mean annual temperature (MAT) has increased by approximately 1.5°C, while the frequency of extreme droughts and heatwaves has also risen significantly [38]. If current trends persist, by 2050 the amount of available water resources may decline by 15–20%, which will inevitably intensify drought stress and pressure on the agricultural sector. Climate inertia and insufficient adaptation could reduce Uzbekistan's rate of economic growth by several percentage points by mid-century, placing the transition to a water- and C-efficient development model among the country's strategic priorities [36, 38].

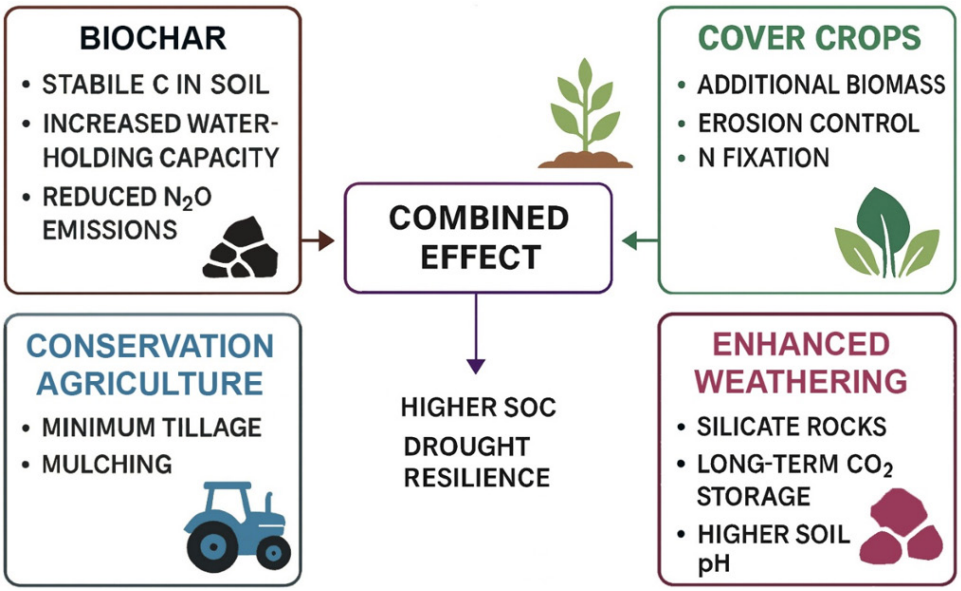


Figure 3. Portfolio of soil-based CDR technologies for arid agricultural landscapes.

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4.2. Soil degradation and depletion of soil organic carbon

The soil cover of the country's agricultural lands is represented predominantly by Sierozems and meadow-Sierozem soils, which have long been affected by irrigation and intensive mineralization of their SOM content. According to FAO data, the average SOC content in the topsoil of croplands in the arid zones of Central Asia is around only 0.4–1.2%, which is 3–5 times lower than the typical values for cropland soils in temperate regions [25, 40]. Depletion of the SOC stock can reduce water-holding capacity, deterioration of soil structure, and an increased risk of erosion and secondary salinization [17, 27].

The most pronounced degradation processes are observed in the Bukhara, Samarkand, and Kashkadarya regions, where compaction of the topsoil horizon, secondary salinization, and disruption of the water regime have been documented. Studies of soils in the Fergana Valley show SOC contents as low as 0.37–0.81%, high salinity and heavy metal accumulation, which further limit the productivity of agro-ecosystems [34]. In arid ecosystems, soil degradation is accompanied by a reduction in SOM stocks and a decline in biological activity, keeping soils "far from saturation" with respect to C while simultaneously constraining their potential as a stable C sink [20, 21]. Table 1 provides comparative data for diverse agro-ecological. Zones on SOC content and types of soil degradation across the agro-ecological zones of Uzbekistan are presented in Table 1.

Table 1

Average soil organic carbon (SOC) content and types of degradation in the agro-ecological zones of Uzbekistan (based on regional and international studies)

Agro-ecological zone	Dominant soil types	Average SOC content, % (0–30 cm)	Major forms of degradation	Source
Fergana Valley *(Central Fergana, Andijan, Namangan, Fergana)*	Serozems, meadow-serozem irrigated	0.37–0.81%	Secondary salinization, compaction, heavy metal contamination	[34]
Irrigated valleys of the mid–Zarafshan and Syrdarya rivers *(Samarkand, Tashkent, Syrdarya, southern Bukhara)*	Serozem soils, gray-brown soils, meadow-serozem, serozem-meadow soils	0.4–0.8%	Secondary salinization, dehumification, erosion	[40, 43]
Desert–steppe regions *(Navoi, Karakalpakstan, Khorezm, northern Bukhara)*	Gray-brown solonchak, meadow-alluvial, desert-sandy	0.2–0.4%	High salinity, wind erosion, low organic matter content	[38, 40]
Transitional rainfed foothills *(Jizzakh, Kashkadarya, southern Navoi)*	Gray-brown, serozem-meadow, solonchak	0.3–0.6%	Loss of organic matter due to tillage, erosion, drought	[40, 43]
Mountain and foothill pastures *(Surkhandarya, Tien Shan, Western Pamir–Alai)*	Mountain brown, serozem	0.5–1.0%	Hillslope erosion, dehumification, overgrazing	[2, 33]

Taken all together, these factors create a "double deficit"— C and water. On the one hand, low SOC levels reduce the soil's capacity to retain moisture, increase yield variability, and heighten sensitivity to drought. On the other hand, the lack of systematic accounting for SOC stock and GHG fluxes complicates the integration of Uzbekistan's agricultural landscapes into national and international climate reporting systems [27, 32]. Therefore, restoring soil C is globally considered a key instrument for simultaneously reducing climate risks and enhancing the resilience of hydric–agricultural systems [23, 25].

4.3. National climate policy and the prerequisites for developing carbon infrastructure

In response to growing climate and water-related risks, Uzbekistan is developing its own C agenda. The Law No. 1073 of the Republic of Uzbekistan "Limiting Greenhouse Gas Emissions (2025)"/ established the regulatory basis for managing the national C balance and implementing climate projects, including soil-based CDR solutions. The Law provides for the phased introduction of systems for emissions accounting and limitation, development of C trading mechanisms and the payment for ecosystem services, and the preparation of national monitoring methodologies [44].

An additional step was Resolution of the Cabinet of Ministers No. 117 of 10 March 2024, which establishes a temporary procedure for implementing emissions trading projects and mandates their registration and verification at the national level [45]. Together with the Uzbekistan Green Taxonomy developed with the support of the World Bank, this forms the framework of future C infrastructure, in which "green" projects in agriculture and land-use management represent one of the priority segments [37].

International initiatives in C monitoring and MRV for soil C (i.e., the GSOC-MRV Protocol and specialized guidelines for SOC accounting in agricultural landscapes) serve as scientific and methodological reference points [32, 35, 42]. This protocol allows Uzbekistan to rely on well-tested approaches when developing its own methodologies and establishing a network of observational sites, including C monitoring sites across diverse agroclimatic zones.

In this context, international and Russian experience in soil re-carbonization (biochar, cover crops, elements of CA) and the implementation of climate projects on agricultural lands serves not only as a ready-made "roadmap" but also provides practical models and evidence of effectiveness [14, 28, 29, 41].

5. PROSPECTS FOR DEVELOPING UZBEKISTAN'S NATIONAL CARBON INFRASTRUCTURE

The contemporary climate agenda places C management beyond the boundaries of a scientific task and is turning it into an instrument of sustainable development and economic policy. Many countries are establishing national C regulation systems that combine monitoring, assessment, and active management of ecosystem C balances [7, 16]. Within this context, soil C is one of the key manageable pools, while C monitoring sites and soil-based CDR technologies form the core infrastructure for monitoring, verification, and certification (Fig. 4).

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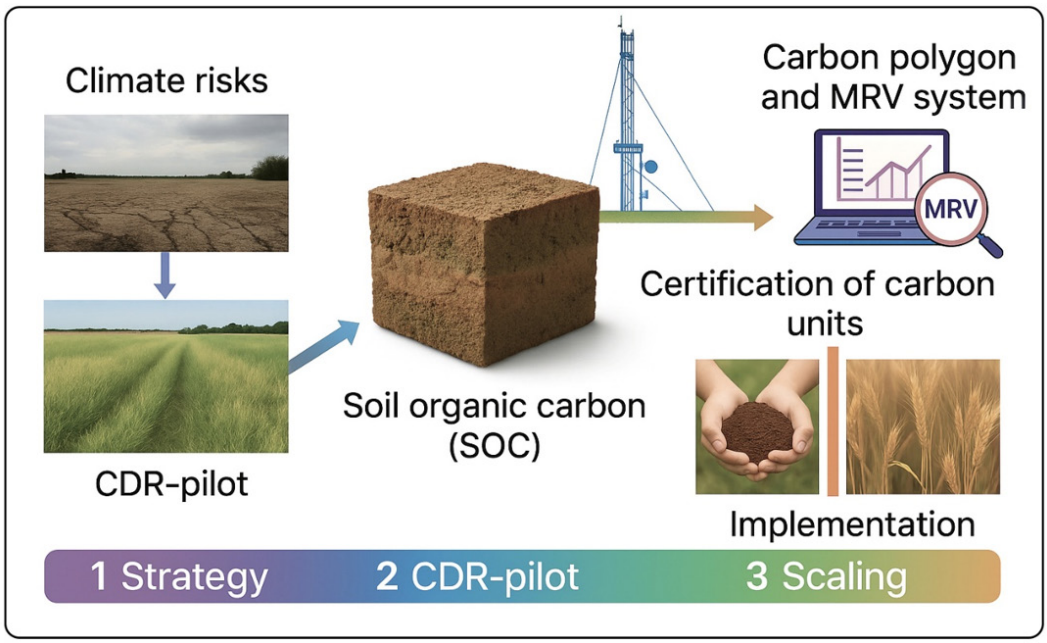


Figure 4. National carbon infrastructure of Uzbekistan: soil organic carbon (SOC) as the core linking climate risks, pilot projects, carbon monitoring sites/MRV systems, and carbon unit certification.

For Uzbekistan, which is vulnerable to both C and drought stress, the development of a comparable infrastructure creates opportunities to integrate climate, water, and agricultural policies. Sequestration of SOC can simultaneously reduce vulnerability of agriculture to drought, improve productivity, and create a foundation for participation in C markets and international climate mechanisms [19, 25].

5.1. Strategic directions for cooperation and institutional development

Given the existing scientific foundation and regulatory prerequisites, several strategic directions can be identified for developing Uzbekistan's national C infrastructure:

1. Establishing a network of carbon monitoring sites. It focuses on a joint development of experimental sites in key agroclimatic zones (e.g., Sierozems of irrigated valleys, rainfed and pasture landscapes, saline soils) using comparable methodologies for measuring GHG fluxes and SOC stocks [3, 32]. The Russian experience with C monitoring sites can serve as a model for selecting design solutions and observation protocols [12, 22].

2. Implementing soil-based CDR technologies. It involves transition from isolated experiments to pilot projects aimed at increasing SOC stocks in agricultural landscapes through biochar, cover crops, and elements of conservation agriculture [14, 29, 41]. It is important to prioritize adaptation of these solutions to arid ecoregions prone to water-resource constraints, including through optimization of irrigation rates and the use of local organic feedstock for biochar production.

3. Developing an MRV system for soil carbon. Establishing a national methodological and technical framework for the MRV of SOC and GHG fluxes based on international guidelines is pertinent to payments to land m managers for ecosystem services [32, 35, 42]. This strategy would include standardized protocols for sampling and laboratory analysis, use of remote sensing and modeling, and specialist training.

4. Creating a competence center and educational programs. It comprises of expanding scientific and educational cooperation among universities and research institutions of Uzbekistan,

Russia, and other countries in the region; establishing joint laboratories and master's/doctoral programs on soil carbon, adopting CDR technologies and the related climate legislation [27, 38]. Such a competence center could become the technical "core" supporting project implementation and methodological development.

5. Integration into global initiatives and markets. Participation in international soil sequestration programs (e.g., the "4 per 1000" initiative), C monitoring networks, and mechanisms under Article 6 of the Paris Agreement helps strengthen confidence in national data, create demand for C units, and attract external investment [13, 24, 30].

Thus, cooperation between Russia and Uzbekistan in the areas of C monitoring sites, MRV, and soil-based CDR technologies can serve as an "accelerator" for building a mature national system of soil C management.

5.2. Roadmap for establishing a system of carbon monitoring sites and soil-based CDR projects

The establishment of a national system of C monitoring sites and soil-based CDR projects should be implemented in stages, combining institutional, methodological, and technological measures. Table 2 presents a consolidated roadmap that reflects the logic of transitioning from problem formulation to the sustainable functioning of Uzbekistan's C infrastructure.

Stage I. Preparatory (2025–2026). The key objective is the political and institutional formulation of the task. At this stage, an interagency understanding of the C agenda is established, responsible authorities are identified, and a coordination mechanism is created. The concept of a national MRV system for SOC and GHG is developed, and cooperation is initiated with international organizations (e.g., WB, FAO, UNDP) on pilot projects. The main risks are associated with delays in coordination and limited human resources, yet this stage defines the framework for subsequent actions [35, 42].

Table 2

Stages in developing a national system of carbon monitoring sites and CDR projects in Uzbekistan

Stage and period	Main directions	Key outcomes
I. Preparatory stage (position setting and coordination), 2025–2026	Formulating a national policy position on the carbon agenda; identifying responsible governmental bodies; preparing the concept of a national MRV system; initiating discussions on pilot sites with partners.	A coordinated interagency understanding of goals and priorities; political backing and a concept for establishing an MRV system.
II. Organizational and methodological stage, 2026–2028	Establishing an Interagency Carbon Council; launching 2–3 pilot carbon monitoring sites; developing national MRV methodologies (GHG, SOC); preparing the regulatory framework for CDR projects and a national carbon unit registry.	An institutionally formalized coordination system; operational methodologies and pilot sites aligned with international MRV standards.
III. Technological and demonstration stage, 2028–2030	Implementing biochar, cover crops, and conservation agriculture technologies; expanding carbon monitoring sites; launching the first CDR projects and verified reports.	Technological readiness and verified results on SOC accumulation; preparation for certification and issuance of carbon units.
IV. Market and integration stage, 2030–2032	Establishing a national carbon unit certification system; launching domestic and export carbon markets; regular reporting under Article 6 of the Paris Agreement.	A functioning carbon unit market; international recognition and Uzbekistan's participation in global carbon mechanisms.

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Stage II. Organizational and methodological (2026–2028). In the second stage, the focus shifts to establishing the infrastructure and methodological foundation. An Interagency Carbon Council is formed, and the first 2–3 C monitoring sites are launched in contrasting agroclimatic zones. Based on international guidelines, national MRV methodologies for GHG fluxes and SOC stocks are developed, along with the legal framework for CDR projects and a national C unit registry [32, 42, 45]. Risks include fragmented data and potential delays in regulatory decisions; the expected outcome is an institutionally formalized coordination system and comparable data from pilot sites.

Stage III. Technological and demonstration (2028–2030). The third stage focuses on testing and scaling technologies. On the basis of C monitoring sites, pilot production areas are established where biochar, cover crops, elements of CA, and, where relevant, enhanced mineral weathering are tested under field conditions [5, 14, 41]. Particular attention is given to adapting practices to arid climates, salinity, and water scarcity. In parallel, a substantial body of MRV data is accumulated, enabling quantitative assessment of the contribution of soil-based CDR technologies to SOC changes and GHG balance. Risks involving natural constraints and investment barriers are validated for technological readiness and preparation for C unit certification.

Stage IV. Market and integration (2030–2032). The final stage assumes a transition from pilot projects to a functioning C market involving the following:1) establishing a C-unit certification system based on recognized standards and national MRV methodologies,2) launching a domestic market, and 3) piloting a participation format in international mechanisms under Article 6 of the Paris Agreement [24, 30]. The primary risk is market uncertainty and initially low liquidity. With successful implementation of previous stages, however, Uzbekistan gains access to additional sources of financing and the status of a reliable partner in the global climate architecture.

Taken all together, the proposed roadmap ensures a consistent transition: from institutional goal-setting and the development of a scientific and methodological foundation to the scaling of soil-based CDR technologies and integration into national and international C markets. This creates a basis for systematic management of soil C stock, water resources, and climate risks in Uzbekistan's agricultural landscapes.

6. CONCLUSION

Soil ecosystems are one of the key components of climate resilience and at the same time a foundation of advancing water and food security. Contemporary research shows that restoring and increasing soil organic carbon stocks enhances water-holding capacity, improves soil structure, and reduces irrigation demand. These factors are critical for advancing the sustainable use of arid regions of Uzbekistan [19, 27]. Even a moderate increase of SOC, about 0.3–0.4% per year to 40-cm depth as per the Paris Accord, can simultaneously offset part of anthropogenic CO2 emissions and reduce risks of soil degradation and drought [25].

International experience emphasizes that the fundamental condition for moving from conceptual declarations to practical climate solutions is the establishment of national MRV infrastructure for soil C and sequestration reducing GHG fluxes [15, 35, 42]. Such systems ensure data comparability, transparency of reporting, and certification of projects; in the context of Uzbekistan, they directly link SOC assessment to the management of water balance in agricultural landscapes.

The roadmap for developing national C infrastructure proposed in this article

outlines a realistic sequence of steps: from institutional goal-setting and the creation of a methodological foundation (2025–2028), through demonstrating the effectiveness of soil-based CDR technologies at C monitoring sites (2028–2030), to the formation of a full-fledged C unit market and integration into international mechanisms under Article 6 of the Paris Agreement (2030–2032) [7, 24]. This configuration aligns Uzbekistan's actions with the global climate agenda and COP cycles.

The practical implementation of the roadmap is based on the combination of biochar, cover crops, and elements of conservation agriculture, whose effectiveness in increasing SOC and reducing GHG emissions has been confirmed by international studies [14, 31, 41]. Biochar and related practices increase SOC and water-holding capacity, reduce evaporation, and improve irrigation water-use efficiency—all crucial in a country where agriculture consumes up to 90% of available freshwater resources [42]. Thus, soil-based CDR technologies provide a "double dividend": a climate dividend (reduced emissions and increased SOC stock) and a water–agricultural dividend (greater yield stability and land productivity).

The creation of a network of C monitoring sites supported by national MRV methodologies and a C unit certification system [30] will enable Uzbekistan to move from fragmented initiatives to systematic management of C and water balances in its agricultural landscapes. Combined with a developing regulatory framework and international scientific cooperation, this article establishes the prerequisites for forming a domestic C unit market integrated into the global climate architecture and "green" finance mechanisms.

Looking ahead, the development of a soil C agenda may become for Uzbekistan not only a tool for reducing climate risks but also the backbone of a green growth strategy. The institutionalization of C projects, participation in global MRV initiatives, and the scaling of soil-based CDR technologies lay the foundation for a transition toward climate-resilient agriculture and rational water use under accelerating climate change.

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