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Review

Monitoring, Reporting, and Verification (MRV) Protocols Used in Carbon Trading Applied to Dryland Nations in the Global South for Climate Change Mitigation

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Abstract

Climate change mitigation involves carbon sequestration that can be supported by Voluntary Carbon Markets (VCMs) and counted as Nationally Determined Contributions (NDCs) in national climate change strategies. Integrating these allows for the determination of greenhouse gas (GHG) emissions and carbon sequestration at the national level. The case for Egypt and other nontropical dryland nations is made in this systematic review article through consideration of monitoring, reporting, and verification (MRV) protocol challenges and initiatives. Improvements are indicated based on the literature, encompassing the academic literature as well as organizational reports and governmental policy documents. Agricultural MRV protocols depending on soil organic carbon (SOC) measurements are specifically considered, delineating the challenges and barriers for SOC MRV methods. Considering the impacts of climate zones affecting soils and providing as much standardization as possible for MRV protocols will improve the accuracy and generalizability of data. Measurements in carbon sequestration monitoring based on SOC MRV protocols need to be informed by soil experts alongside climatologists and policymakers in a multidisciplinary approach.

Keywords: carbon credits; carbon capture and storage; agricultural soils; hyperarid, arid, and semiarid regions; Middle East and North Africa (MENA) region

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1. Introduction

Voluntary carbon markets (VCMs) have emerged since the mid-1990s as self-regulated bodies separate from the carbon markets set up by governments in response to the 1997 Kyoto Protocol [1]. They work with private certification standards to produce carbon credits for carbon dioxide (CO_2) equivalent tons of greenhouse gas (GHG) emissions. The 26th United Nations Climate Change Conference (COP26) opened to carbon credits generated by the private market to be offset within the regulated market. VCMs, as a form of private environmental governance (PEG) [2], offer viable solutions only if they are backed by high-quality credits that represent valid GHG emissions reductions. Therefore, according to [2], public–private hybrid forms of environmental governance for VCMs could facilitate improved performance through government intervention and public governance support for the private carbon marketplace.

Carbon Emission Reduction Certificates (CERCs) are tradable financial assets that equate to reductions in GHGs and are issued by entities representing projects aimed at reducing GHG emissions, but subject to approval by authorities. Each CERC corresponds to the reduction of 1 Mt CO_2e or 1 carbon credit. It is anticipated that global carbon credit trading can reach 250 billion USD by 2030 [3]. However, CERCs must undergo a rigorous verification and validation process in accordance with several decrees, such as the Financial Regulatory Authority (FRA) Decree No. 31 (2024), which outlines the procedure for registering Carbon Emission Reduction Projects (CERPs). Applicants register their project in the CERP database by applying to the FRA, which subsequently issues a registration certificate. The issuance of CERCs can take between 1.5 and 2 years [3]. This process comprises standards and procedures for verification and validation, and is audited by verification bodies at local and international levels before being listed in the FRA's registry.

1.1. Defining MRV Protocols

Monitoring, reporting, and verification (MRV) protocols constitute a set of rules and procedures used to quantify, track, and verify GHG emissions reductions and removals. These specifically incorporate the following components:

(1) Monitoring: This involves using scientific methods and models to quantify the amount of CO_2 removed by a project, and includes techniques appropriate for the specific carbon removal method.
(2) Reporting: The measured data are compiled and reported according to established protocols, including detailed information about the project, methodology, and results.
(3) Verification: A third-party verifier assesses the project's data and methodology to ensure it meets the requirements of the specific MRV protocol, which includes an independent validation of carbon removal claims.

MRV protocols ensure transparency and comparability in climate change mitigation efforts, enabling the accurate assessment of projects and policies aimed at reducing environmental impact. Authors [4] have deployed MRVs to encompass several aspects, encompassing quantification, structures, and requirements, ensuring that quantified credits are integrated.

1.2. Background to MRVs

Most carbon credits retired on the VCM encompass projects that avoid or reduce emissions, as opposed to removing carbon [5]. Accordingly, in 2023, actual carbon dioxide removal (CDR) credits accounted for <10% of total credits sold on the VCM ([5], p. 124). Between 2013 and 2022, models aligned with estimates of the Global Carbon Budget suggest reductions between 1160 and 2230 Mt CO_2 per year from afforestation/reforestation, an average reduction of 1860 Mt CO_2 per year ([5], p. 124). However, when reemission of CO_2 through the decay of existing wood products is considered, the net sink amounts to substantially less (reductions of 332 Mt CO_2 per year) over this period ([5], p. 124). Therefore, more than afforestation/reforestation methods are needed for CDR.

Existing MRV methods vary by country, and overlapping protocols exist, making for an "MRV ecosystem" ([5], p. 182). This means that most protocols have a shared foundation, or common framework, that brings both risks and opportunities. Methodological weaknesses or incorrect assumptions in the common framework, however, could resonate through the entire MRV ecosystem. This foundation encompasses two predominant structures influencing measurement and reporting methods: (1) national GHG inventories under the United Nations Framework Convention on Climate Change (UNFCCC) and (2) VCM methods guiding project-level accounting [5]. Measurement and reporting standards are set in the Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories that stand up to international scrutiny.

1.3. 2006 IPCC Guidelines

These guidelines are essential for providing procedures at the national level for countries to estimate GHG emissions and removals (including soil organic carbon or SOC) that are periodically reported to the UNFCCC. A three-tiered methodology exists for accounting for and monitoring SOC and net GHG emissions (refined version available from https://www.ipcc-nggip.iges.or.jp/public/2019rf/index.html, accessed on 15 October 2025). While IPCC-Tier 1 is the default approach and deploys average emission factors for large global ecoregions, Tier 2 uses national- or regional emission factors. Field measurements or scientific literature provide superior accuracy. Tier 3 is more detailed and complex and usually includes (process-based) models that rely on field-based data that can be deployed to calibrate or validate models.

1.4. Rationale and Research Question

The MRV protocol is an essential component of certification, since it provides a framework for assessing CDR claims. Questions remain concerning durability, double counting/double issuance, quantification, and additionality ([5], p. 186, Box 10.1). Accordingly, double counting/double issuance is being addressed under Article 6.4 of the Paris Agreement, which seeks to establish a centrally run crediting mechanism for project activities. Currently, there are some 102 MRV protocols spanning 16 CDR methods ([5], p. 193). Their Table 10.2 (2003–2023) shows a total of 21 biological MRVs covering soil carbon sequestration in croplands and grasslands (p. 194), of which 15 are voluntary or international; most (11) are avoidance and removal rather than only removal. This (soil carbon sequestration in croplands and grasslands) ranks second among afforestation, reforestation, agroforestry, and forest management—which have a total of 34 biological MRVs. Therefore, agricultural carbon sequestration in soils is a growing area in climate change mitigation.

Different guidelines and methodologies for MRV have been listed by Batjes et al. ([6], p. 9, Table 2). These authors focused their review on a selection of guidelines which they recognized as most relevant based on their expertise. Among the major registries in the VCM, they included the American Carbon Registry, Verified Carbon Standard (Verra), Climate Action Reserve, and Gold Standard Impact Registry. The current review focuses on soil carbon sequestration MRV protocols, which have been growing in number ([5], p. 195, Figure 10.1) since at least 2014.

This review article examines carbon trading MRV protocols currently in use in carbon trading in Egypt and the MENA region, encompassing nontropical drylands in the Global South. Egypt was selected as a case study because of its extensive agricultural land use and the severe restrictions that climate change is placing on its resources. It compares well to other countries in the region, such as Morocco and Iran, and can represent the region. However, it should be noted that Saudi Arabia is making headway in the carbon market and sustainability more broadly through its Vision 2030, which includes investments in advanced carbon capture technologies and in developing a regulated carbon credit market (see https://arab.news/gv9wb, accessed on 10 November 2025). According to this source, Saudi Arabia launched its first carbon trading exchange, underscoring its commitment to sustainability and bringing together 22 local and international companies (offering 2.5 million carbon credits originating from countries like Bangladesh, Brazil, and Ethiopia). The Kingdom is prioritizing quality and transparency in its regional market within the Gulf Cooperation Council (GCC), developing standardized frameworks that are in line with global benchmarks to ensure consistency and reliability. It is investing in green technology, including drones, satellite imaging, and AI, to accurately measure baselines and life cycle project measurements, contributing to transparency as well as accountability. Saudi Arabia's carbon credit market is driven by large-scale projects as well as cutting-edge technology, in addition to its commitment to transparency.

The emphasis will be on agricultural carbon removal technologies, with MRV that ensures the integrity of carbon credits issued for agricultural technologies to remove CO_2 from the atmosphere. Such an MRV protocol enables climate action and is essential for tracking progress toward climate goals, allowing for informed decision-making and ensuring that carbon removal efforts contribute to achieving net-zero emissions. Therefore, this systematic review contributes to the work on sustainability by way of carbon emissions reductions in agriculture and climate change mitigation at the national–regional scale.

Petrochemical companies in the MENA region are demanding carbon credit projects for trading. This systematic review ultimately aims to answer the research question: Is there a case for SOC MRV protocols to be adopted in nontropical dryland nations for carbon trading? To answer this question, it is necessary to (1) identify the challenges and (2) seek out tangible future directions. Even though arid soils are carbon-depleted in this region, agriculture is a major industry in the Global South and can substantially create economic opportunities. The unique contribution of this paper is to systematically address the challenges and improvement pathways for the MRV adaptation framework for hyperarid, arid, and semiarid regions, drawing on practical insights from the Egyptian case for the MENA region.

2. Materials and Methods

The literature search was executed on 6 July 2025, in Google Scholar to access a breadth of literature, including nonacademic (organizational and government) documents. Literature selection was based on the search string:

- "carbon sequestration" AND "agricultural land" AND "climate change mitigation" AND "Global South" AND "arid land" OR drylands.

The search produced 273 results in Google Scholar (Figure 1), with additional online sources and papers derived from existing items. Notably, there were no constraints on time or type of article, although both patents and citations were excluded. Of the outputs, it was possible to download PDFs for 113 items, which were then manually processed according to the selection criteria. This included MRV protocol references that addressed rural areas in the Global South and arid land or drylands, excluding unpublished theses.

The downloaded reports (PDFs) had to (1) be for countries with drylands situated in the Global South and (2) address MRV protocols for carbon credits or trading (3) associated with carbon sequestration for climate change mitigation in agricultural land. For example, energy-related MRVs were excluded since the focus was on cropland management practices used to sequester carbon in soils as SOC. Several studies addressed forests (e.g., afforestation, reforestation, agroforestry), but because of the focus on measuring SOC in agricultural lands, these studies were excluded. Agroforestry could have been included to expand the studies, but 53 items were thought sufficient for an in-depth review. Besides, the overarching ambition was to focus on SOC MRV protocols representing the growing market.

Relevant PDFs were uploaded to a Zotero bibliographic database. Duplicate items were merged. Notes were added regarding the relevance of each item, and the output was provided as a report for processing. These annotations were the basis for writing this review article. It should be noted that these PDFs included a variety of sources, such as journal articles as well as reports, books, book chapters, and more.

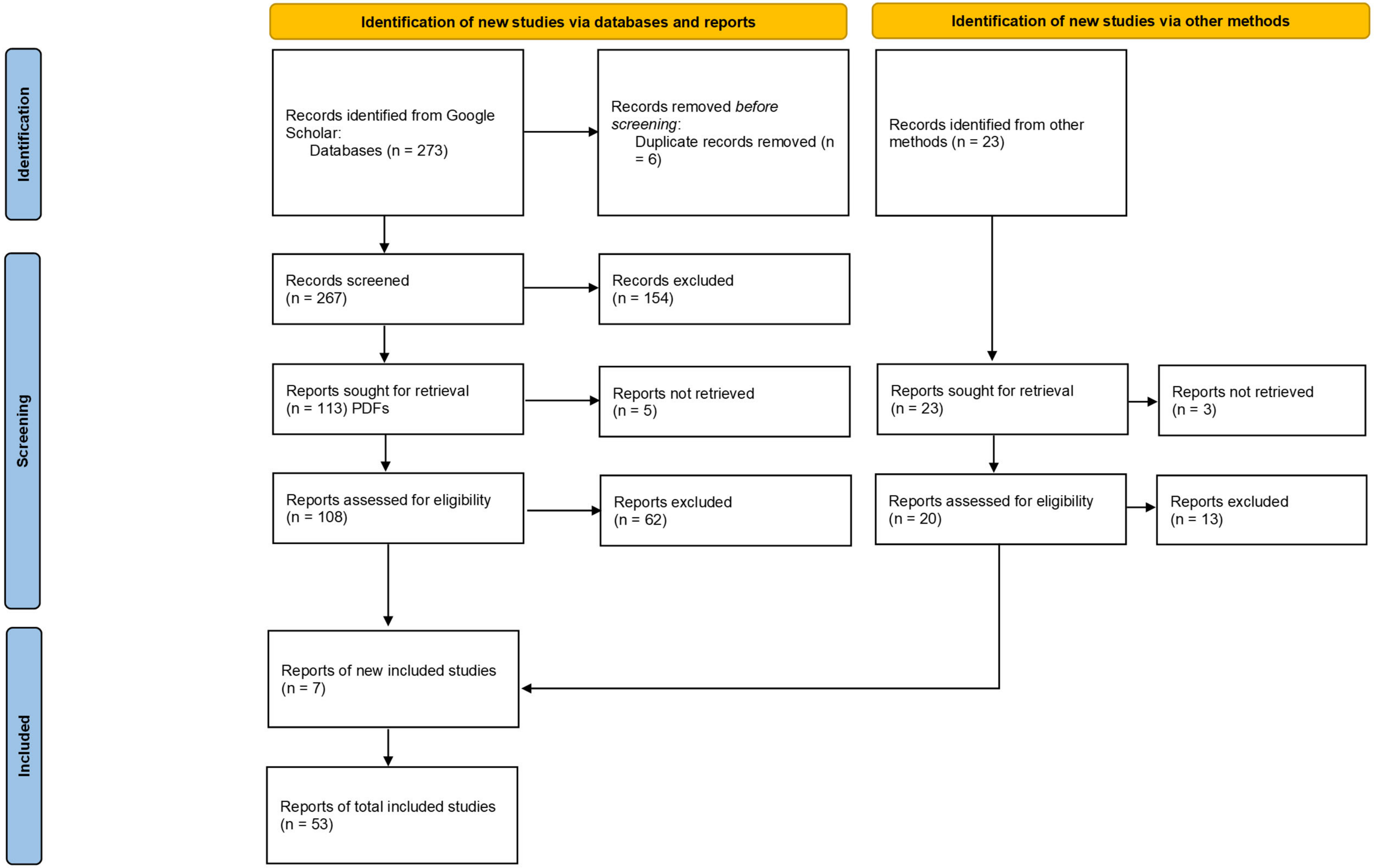

Figure 1. PRISMA flow diagram (modified from [7]). This work is licensed under CC BY 4.0. (To view a copy of this license, visit https://creativecommons.org/licenses/by/4.0/, accessed on 13 October 2025).

3. Results

In September 2009, there was only one larger carbon trading scheme (Chicago Climate Exchange) that included agricultural soils, and it focused on no-till farming [8]. The initial emphasis on no-till agriculture was advocated by the Food and Agriculture Organization (FAO), which called on the UNFCCC to adopt it on a large scale and to recognize soils as carbon sinks. The 2006 IPCC Greenhouse Gas Inventory Guidelines estimated that converting conventional to no-till systems would lead to 10% more sequestered carbon in the soil, although the error margin of this estimate was large (4–50%), depending on the climate zone. More recently, in its Assessment Report 4, there was the consideration of soil disturbance leading to carbon losses through enhanced decomposition and erosion [8]. Depth also mattered: Measurements deeper than 30 cm in no-tillage found no consistent buildup of SOC at local–regional scales. For agriculture, projects have focused on manure management, methane (CH_4) reduction from rice cultivation, CH_4 reduction from ruminants, and nitrous oxide (N_2O) reduction from fertilizer application ([9], p. 9).

3.1. Challenges of SOC MRV Protocols and Some Suggestions for Improvement

Soil carbon sequestration involves the transfer of CO_2 from the atmosphere into soils by way of crop residues and other organic solids [10]. Soil carbon sequestration is cost-effective as a climate change mitigation strategy, especially when cobenefits like improved soil health are considered [10]—particularly for no-tillage and cover cropping soil management practices for carbon sequestration. However, according to these authors, more research is needed to develop robust MRV protocols and improve our understanding of the long-term dynamics of soil carbon storage under different environmental conditions and management practices.

It is anticipated that the agricultural sector will play a key role in generating carbon credits through production methods that sequester carbon, although farmers are not committing to support carbon credit generation [2]. Research by Figueredo [11] stipulated that there are generally positive attitudes among farmers toward farming practices associated with "carbon farming" because of their cobenefits. However, different studies have reported that farmers are skeptical about the feasibility of carbon farming. These felt constraints concern a lack of information, potential bureaucratic hurdles, inadequate training, and long-term commitment [11]. Due to local conditions and the heterogeneity of farms, the benefits of carbon farming are not uniform, especially for smaller farmers and those with less fertile soils, as evident in the MENA region. Several studies on farmers' perceptions of carbon farming schemes find that economic incentives drive farmer involvement [11]. Nevertheless, financial compensation may be inadequate, and the fairness and transparency of market-based mechanisms are a concern.

There exist challenges to carbon farming, even though there has been much progress in the last 20 years, including MRVs [12], which impacts confidence and assurance in carbon sequestration. Measurement protocols are complicated by the spatial scales of measurement as well as by the payment mechanisms and incentives used to support farmers. For example, MRV options include direct sampling of soil on individual farms, aggregate sampling across many farms, modeling and remote sensing approaches, and others [12]. The chosen approach will significantly affect MRV costs and the uncertainty associated with the outcomes.

The next subsections identify challenges in MRV protocols that could also affect SOC MRV systems. Much of the literature addresses the first component of monitoring, making it the lengthiest subsection. Current MRV methods include direct soil sampling, remote sensing, and modeling approaches—each with its own strengths and limitations.

3.1.1. Monitoring

SOC represents a standard for measuring carbon stocks. According to Batjes et al. [6], soils represent the largest terrestrial reservoir of organic carbon. These authors found the greatest challenge to developing a unified MRV system is this initial component involving measurement or monitoring. However, there is disagreement about the ability of regenerative management practices to sequester sufficient SOC to mitigate climate change. Such authors [13] found that monitoring higher sampling densities of 4 ha/sample and field numbers of 30 pairs of fields, along with simulated SOC stock accruals of 3–5 Mg C/ha over 10 years, can collectively lead to accurate estimates of management effects on stock changes at the project level. Importantly, controls need to be in place to test for treatment effects.

Having 30 cores may not be sufficient to detect modest SOC changes due to management in heterogeneous landscapes [14]. Accordingly, to reduce error and improve the reliability of SOC offsets and improve protocols, it is necessary to (1) perform power analysis, considering spatial heterogeneity, when determining sample size; (2) use nonparametric tests, including confidence intervals; and (3) employ dry combustion, ideally processing all samples in the same laboratory.

Authors like Paustian et al. [15] have noted that, with the potential for annual stock changes of $\leq$1% of existing stocks, where there is a moderate sampling density, measurement intervals of at least 5 years are required to detect statistically significant cumulative SOC stock changes. The stock change in SOC at specific benchmark locations (with Global Positioning System or GPS coordinates recorded) can be resampled over time. Because spatial soil variability occurs at fine spatial scales, direct field measurements in schemes that optimize sampling intensity to reduce uncertainty can reduce costs.

Spatial and temporal economies of scale can be had with projects that have 1000s of fields. These require SOC change measurement in only ~10% of fields [16], and can yield a competitive return in 5 years. Measure-and-remeasure is cost-effective in both market and nonmarket SOC projects at scale. They provide valuable data for independent validation of the accrual rates estimated by biogeochemical models.

There are also issues with measuring induced SOC change at annual-decadal scales, which may not be detectable with enough confidence due to the slow accrual rate and large spatial SOC variations [17]. Additionally, these programs need to account for potential increases in other potent GHGs like N_2O and CH_4 accompanying changes in cropland management. According to these authors, standardizing across regions (a regional framework) would allow for consistency while allowing for the incorporation of region-specific parameters.

Stock measurements are executed using either horizon-based or continuous core sampling [18]. Methodological differences could stem from whether a horizon scraping or core is used for sampling. Their [18] research indicates a substantial reduction in differences when using the equivalent soil mass calculation (ESM) approach, rather than a fixed depth (FD). FD and ESM estimates of stock change can differ greatly, with much of the difference attributable to changes in the bulk density [19]. The latter (FD) measurements can result in error due to changes in soil bulk density, as well as due to the fact that sampling to 30 cm depth excludes a large portion of the soil profile's SOC stock [19]. However, most MRV protocols do not specify a sampling method, requiring only that sampling be executed to depth.

Although measuring SOC remains a challenge, it is vital that MRV protocols demand that users measure it rather than rely on regional values, which can potentially overestimate carbon stocks by as much as 2.5$\times$ ([20], p. 5). When scaling up to the international level, it is important to develop an international standard for measuring SOC. The standardization of soil depth is an important factor, for example, that can vary from a minimum of 20–50 cm depth depending on the soil carbon credit protocol (see Table 1 in [20], p. 4), with a widely ranging recommended depth of 20–100 cm. Furthermore, some of these protocols (e.g., Nori, $GStd_{mod}$, PVivo, CFT, LBC) require only modeling and no sampling, and in many cases modeling can be used to establish the baseline. For modeling soil carbon credits, the initial SOC stock is not always required [20]. Accordingly, information regarding farming practices is uneven in detail, for example:

- LBC, PVivo—discount tillage information.
- CFT, PVivo, the IPCC-based version of $GStd_{mod}$—do not include crop rotation; the complexity of the rotation, together with the yield of each crop.
- $GStd_{mod}$, CFI, PVivo—cover crops are not explicitly required to model SOC changes.

There are also differences in sampling frequency (most require 5 years) and issues of surface homogeneity in hectarage represented by the samples, with several unspecified. Additionally, there are different procedures allowed to quantify SOC, producing differences up to 20% [20].

A paper by Ellis and Paustian [21] argued for the importance of incentivized practice adoption on as much land as possible (e.g., commercial farms). Because process-based models are parameterized on data based on a constrained number of long-term experiments, they may not reflect working farm outcomes. For this reason, these authors [21] presented a collaboration with commercial producers in the American Midwest, which directly measured and modeled SOC stocks at the field scale (with data from 22 farms located in Iowa and southern Minnesota).

According to Kuhnert et al. [22], field and farm scales are most relevant to an MRV scheme. Field measurements are essential, although they can be laborious and costly. Existing MRV protocols often lack clear measurement standards. For this reason, modeling is adopted as an alternative—along with others—appearing in Table 1. Using a combination of methods, such as both field data and modeling, can compensate for their respective shortcomings and improve the results.

Table 1. Alternative measurement and monitoring methods to field sampling.

Method	Dis/Advantages
Biogeochemical models	Include errors and uncertainty based on the assumptions used and underlying concepts [22] Need to be calibrated and validated, which requires data [22]
Ecosystem models	Enable larger scales, but models need to be unbiased and adequately predict SOC changes with known uncertainty [23] DayCent-CR version of the DayCent ecosystem model is a credit-ready version that meets some guidelines, e.g., Climate Action Reserve's Soil Enrichment Protocol [23]
Hybrid approach	Modeling in DeNitrification-DeComposition (DNDC) with life cycle carbon Footprint showed reduced GHG emissions with agricultural residue utilization
Life cycle assessment (LCA)	LCA can provide critical insights into baselines, uncertainty, additionality, multifunctionality, holistic emission factors, overlooked carbon pools, and environmental safeguards [24]
Remote sensing	Including (1) spaceborne, (2) airborne, and (3) terrestrial remote sensing based on imagery acquired using various methods—e.g., satellites, airplanes, and unmanned aerial vehicles (UAVs) like drones, respectively [25] Nondestructive and can cover large areas, including those that are inaccessible, but can be limited to the first few cm of topsoil and measurements can be obscured by vegetation cover, and unable to measure belowground biomass [25] Low prediction accuracy of soil carbon, although it can be deployed as a collection of auxiliary data used for model-based estimates of carbon sequestration [25]
Mid infrared (MIR) spectroscopy	MIR spectroscopy has excellent performance in SOC measurement, e.g., root mean square error (RMSE) 0.10–0.33% across seven sites, with the same level of statistical significance ($p < 0.10$) for management effect using both laboratory-based % SOC and MIR estimated % SOC [26] Large existing MIR special libraries, e.g., United States Department of Agriculture-Natural Resources Conservation Service (USDA-NRCS) Kellogg Soil Survey Laboratory MIR spectral library—can be operationalized for carbon monitoring [26]

It should be noted that using such alternative techniques as remote sensing in arid lands could improve issues associated with obstructions in imagery due to reduced cloud and vegetation cover. However, this (remote sensing) alternative is limited to 30 cm depth and could not generate measurements of deeper SOC content (Table 2). Furthermore, restricting SOC sampling to within 30 cm of the surface will greatly underestimate SOC measurements for dryland soils (see Table 2 in [27]). Therefore, a tradeoff exists between more easily (and more cheaply) sampling to 30 cm than deeper sampling, which requires core extensions to reach depth and incurs additional fieldwork costs. Nevertheless, the current standard in the literature remains monitoring to a depth of 30 cm. It should be noted that the 30 cm depth standard for agricultural "topsoils" is affected differently in arid regions, where traditional implements (e.g., unmechanized techniques) can be deployed to work soils.

Table 2. Comparison of the techniques used to generate SOC measurements.

Method	Cost	Scale	Spatial Resolution	Limitations
Traditional direct sampling	Field, laboratory	Local–regional	High	High variance
Modeling	Software, experts	Local–global	Medium	Uncertainty
Remote sensing, incl. spectroscopy	Data access	Regional–global	Low	30 cm depth

Differentiated MRV designs are needed in arid regions. For example, model inputs for determining turnover rates in RothC require information including climatic data, clay content, and vegetation cover, such as the decomposability of plant material inputs, soil cover (bare versus vegetation), and inputs of plant residues, plus farmyard manure data, if available [28]. Climatic data, clay content, vegetation decomposition and inputs, and the use of farmyard manure will differ in arid regions. There is potential for remote sensing here due to sparse vegetation cover, providing an unobstructed view for remote work.

Therefore, key contradictions exist in arid regions, such as shallowly worked topsoils that are easily monitored due to unobstructed views. Conversely, deeper sampling holds significant potential, especially since there are stocks of inorganic carbon deeper in these soils [6], although deeper monitoring incurs higher costs. These points call for the development of compromise solutions for this region.

The availability of different MRV approaches and the acceptance of buyers for measurement error and uncertainty will influence the ability of producers to trade in SOC. The creation and funding of a global soil information system has been suggested [15,29], which could provide data to lower the costs of SOC MRV and support carbon trades. Ultimately, monitoring should be executed by professionals in the field (e.g., soil scientists).

Mercer and Burke [30] have cautioned against a lack of International Organization for Standardization (ISO) standard reference in their methodologies, as well as missing detailed MRV process documentation by these firms to ensure that offsets are credible, additional, and permanent. Mercer et al. [31] outlined MRV protocols relevant to soil carbon in croplands and grasslands for CDR projects that have been operational for 3–4 years. To date, they have measured >5001 tons removed, including Verra, Social Carbon, and Article 6 bilaterals, with their own developed protocol. However, the credibility of carbon credits depends on additionality and permanence in carbon sequestration. Agricultural MRV protocols focus on credits generated from SOC sequestration (rather than credits from avoided or reduced GHG emissions). Although, for instance, the study by Wang et al. [32] quantified and substantiated the GHG emission reduction potential of agricultural production, advocating its potential to intensify agricultural production.

3.1.2. Reporting

Reporting is a necessary part of maintaining transparency in the MRV process. The Enhanced Transparency Framework (ETF), for example, under the Paris Agreement parties need to report their progress toward Nationally Determined Contributions (NDCs). Carbon markets must feed into this reporting system [33]. These authors [33] espoused that having a centralized data platform accessible to parties and observers can enhance transparency. This is especially pertinent in the Global South, where there is a need for funding, institutional support, and training to implement robust MRV systems.

According to Oldfield et al. [34], misconceptions occur about the SOC MRV protocol design and implementation, where there is a lack of detail in MRV documentation and about the scale of project implementation. Today's protocols are "living documents" (works in progress) used to guide credit generation [34]. Therefore, many protocol documents are in their early versions and will evolve based on feedback from producers, credit buyers, and scientists.

3.1.3. Verification

Authors [35] have espoused that digital MRVs can implement and develop a carbon data quality assurance system. Accordingly, such a digital MRV system can incorporate digital technologies, such as satellite remote sensing, continuous emissions monitoring, Big Data, the Internet of Things (IoT), and blockchain technology, which can facilitate precise measurement and tracking of carbon emission data and establish a foundation for digital MRV development. This can improve traditional manual MRV calculation approaches, which rely on bottom-up calculations and self-reported data [35], which introduce biases and inaccuracies and compromise the reliability and integrity of collected information. Manual data entry and aggregation can also contribute to human errors and delay obtaining reliable datasets.

3.2. The Case for Egypt

Egypt ratified the Paris Agreement in 2015 and has an NDC that focuses on sustainability in agriculture as well as the environment at large, including water resources, energy, and land management priority areas. Egypt is modernizing its agriculture, including irrigation systems, restricting water-intensive crops, and land reclamation projects [36]. Accordingly, further projects include Sustainable Agriculture Investments and Livelihoods (SAIL 2023) and Building Resilient Food Security Systems to Benefit the Southern Egypt Region—the latter in response to supply shortages for wheat due to the war in the Ukraine.

3.2.1. Egypt's National Climate Change Strategy (NCCS) 2050

According to the Summary for Policymakers: Egypt National Climate Change Strategy (NCCS)—2050 [37], sectors such as agriculture represent a significant percentage of the total GHGs, contributing 9% in 2018 (p. 16). Accordingly, the agricultural sector is sensitive to climate change, affecting food security—and, therefore, economic growth. According to this report, adaptation programs for agriculture alone will cost 52,400 million USD between 2022 and 2050 (p. 45, Table 6.2) and constitute 46% of the total budget. It comes second in cost next to irrigation and water resources, which account for 52% of the total budget. Together, these linked resources account for 98% of the budget costs.

3.2.2. Egypt's Second Updated Nationally Determined Contributions

Egypt ratified the UNFCCC in 1994—it was among the first countries to respond to the threats of climate change. Egypt submitted its NDCs in November 2015, and subsequently made its first NDC on 29 June 2017 [38]. The country submitted its initial (1999), second

(2010), and third (2016) national communications to the UNFCCC. In 2019, it submitted its first Biennial Update Report (BUR), and most recently, at the end of 2024, it submitted its fourth national communication to the UNFCCC. These reports encompass envisaged plans and adaptation-mitigation measures toward achieving its commitments under the UNFCCC. The report on Egypt's Updated Nationally Determined Contributions [38] is an update to the first NDC and covers 2015–2030, including its Sustainable Agricultural Development Strategy toward 2030 (SADS 2030).

Some three-fifths of Egypt's food production is secured from agricultural lands located in the Nile Delta region ([38], p. 6). Cultivated areas are expected to be reduced to ~0.95 million acres (or ~8.2% of the Egyptian cultivated area) by 2030 due to climate change impacts. Accordingly, it is anticipated that the Delta will lose at least 30% of its food production by 2030 [38]. Further impacts from increasingly frequent droughts and floods will lower crop and livestock productivity. Agriculture consumes ~80% of the total water budget, affecting the livelihoods of >25% of the labor force in Egypt working on agricultural activities [38]. Millions of people will be beneficiaries of agricultural strategies in agriculture ([38], p. 23), especially in northern areas bordering the Mediterranean coast. Anticipated crop yield increases can range from 10–15% (p. 23).

3.2.3. First Biennial Update Report (BUR) and Fourth National Communication

Egypt's agriculture is vital for its regional food security and national economy. Indeed, water resources, agriculture, and livestock are among the key adaptation sectors. Even though its arable land is concentrated in the Nile Valley and Delta, there are additional reclaimed desert areas that encompass some 3.5 million acres of desert [39]. The Agriculture, Forestry, and Other Land Use (AFOLU) sector accounted for 41,561 Gg CO_2e of Egypt's national GHG emissions in 2022, with a share of 10.76% of the total inventory [39]. Emissions were derived from agricultural soils as well as field residue burning, manure management, rice cultivation, and enteric fermentation. According to the report, AFOLU sector emissions reductions in 2019 were attributed to reduced use of synthetic fertilizers and urea. Overall fluctuations in emissions vary according to fertilizer quantities and reflect declining livestock numbers resulting from higher feed prices. The sector's GHG emissions were distributed across three gases: N_2O, CH_4, and CO_2, with the former (N_2O) being dominant. According to [39] (p. 105), N_2O accounted for 58% of Egypt's GHG emissions in the AFOLU sector in 2022. Second (38%) was CH_4 from enteric fermentation in livestock and rice cultivation. Last (4%) was CO_2 from biomass burning and liming activities. However, it should be noted that farmers use agricultural residues for bioenergy, composting, and other sustainable activities, resulting in no biomass burning on agricultural lands.

As noted in the BUR, prior to its submission to the UNFCCC, GHG emissions from the AFOLU sector were measured using the Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories and the Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories. Three sources of N_2O emissions in Egypt's agricultural sector were recognized ([39], p. 109), that included the following:

- Direct N_2O emissions—from agricultural soils, including nitrogen-fixing crops, crop residues, fertilizers, and animal waste;
- Direct N_2O emissions—soil emissions from livestock production; and
- Indirect N_2O emissions—runoff, nitrogen leaching, and volatilization from agricultural activities.

3.2.4. Egypt's Carbon Trading Regulations and Guidelines

Egypt's new carbon trading market was recently launched by the Prime Ministerial Decree No. 4664 of 2022 [3], which paved the way for a carbon trading platform at the

Egyptian Stock Exchange (EGX). Thus, the FRA introduced regulations to create a robust framework for listing/delisting, issuance, accreditation, and trading CRECs. Voluntary carbon registries acknowledged by the International Carbon Reduction and Offset Alliance (ICROA) are fully compliant with FRA conditions without the need to follow conditions mentioned under the FRA Decree No. 30 of 2024 [3].

Egypt's VCM aligns with its Vision 2030 and the National Climate Change Strategy 2050, which seeks to balance economic growth and environmental stewardship by driving sustainable development while committing to climate change mitigation. All government entities, businesses, and project developers are required to notify both the FRA and the Ministry of Environment about projects for which CERCs will be issued. Several decrees have been issued by the FRA to establish and regulate the VCM (Table 3).

Table 3. Decrees issued by the FRA to establish and regulate the VCM in Egypt.

FRA Decree No.	Year	Details
57	2023	Establishes a Carbon Credits Supervision and Control Committee
163	2023	Lists entities that verify and attest to CERPs
30	2024	Sets standards for transparency, data security, and governance in accrediting voluntary carbon registries; ensures unique identification and traceability of each CERP
31	2024	Outlines the rules for listing/delisting and trading CERCS on the EGX
1732	2024	Outlines the conditions for brokerage firms to trade CERCs

Egypt made its first-ever carbon trade on 13 August 2024 in the newly launched African VCM. The EGX announced the transaction, and it was announced on the Egyptian Climate Exchange website (https://www.egcx.com.eg/single_post/33#:~:text=In%20a%20historic%20step%20towards,transaction%20value%20to%20520%2C000%20EGP, accessed on 8 July 2025). More specifically, it involved the sale of 500 carbon emission reduction certificates (each at EGP 1040) for a total value of EGP 520,000. The seller was the Egyptian Association for Biodynamic Agriculture, and the buyer was Isis Food Manufacturing Company. This exchange represents a significant milestone following Egypt's earlier establishment of the market during the COP27 conferences in 2022.

3.3. Lessons from (Other) Nontropical Dryland Nations

Differences in MRV protocols are a risk because this can lead to nonequivalent carbon credit creation [25], which can undermine trust in market integrity. Therefore, it is necessary to glean lessons from other nations. For Egypt, the lessons are most relevant from nontropical dryland nations in the Global South, which will be addressed in this section.

The national focus in this section is on countries in the Global South, especially those located in nontropical drylands in the MENA and CWANA (Central and West Asia and North Africa) regions. Three of these frequently appear in the published literature, including African countries (e.g., Ethiopia, Kenya), China, and India.

3.3.1. African Countries

Africa's carbon farming projects are based on frameworks provided by verification bodies (e.g., Verra, Gold Standard, Plan Vivo). According to Schilling et al. [25], as of 2023, six projects in Africa are being developed under Verra's VM0042, which was approved in 2020. The methodology has moved away from purely modeled data toward hybrid modeling and soil sampling to reflect a demand for more rigorous methodologies for carbon credit projects.

In 2010, some 497 projects in AFOLU were identified around the world, of which 20% were based in Africa [40]. Accordingly, however, this is reduced to only 3.5% when excluding projects that were not registered under any carbon trading schemes. For example, the then 10 African soil carbon projects in Kenya, Madagascar, Mauritania, and the Sudan were not part of carbon trading schemes [40]. Africa signed its first soil carbon deal in November 2010, which benefited Kenyan farmers through the World Bank Biocarbon Fund [40]. The implementing organization may not be the land steward. For example, World Vision developed a project in Ethiopia that converted 503 ha of grass and cropland to forest that targeted some 3000 farmers.

In Kenya, carbon credit initiatives have been running since 2014, and are largely community-based [41]. The main objective of these initiatives is to reduce the costs of carbon farming to increase the income of local communities. For example, the Northern Kenya Rangeland Carbon Project started in 2012 seeks to generate additional revenue for farmers in 14 communities through conservancies from grassland soil cultivation. The project removes and stores 50 Mt CO_2e over 30 years, with the Northern Rangeland Trust (NRT) selling carbon credits on behalf of the communities certified by Verified Carbon Standard (VCS) ([41], p. 32). Accordingly, with demand exceeding supply for carbon credits, there is much potential for developing carbon credits in the AFOLU sector. Indeed, the AFOLU sector can become a major supplier of carbon credits with a reduction potential of GHG estimated to be ~23% ([41], p. 34). In Kenya, it is anticipated that major policy changes will intensify carbon market activities and regulate carbon emissions.

3.3.2. China

China's national emissions trading market was launched on 16 July 2021, and emissions trading in China has concentrated on the power industry because of data availability and preparedness [35]. During its first compliance phase, there were concerns about the falsification of carbon emission data, as well an inadequate MRV system was exacerbated by insufficient legislation, technical innovation obstacles, and limited public awareness [35].

For emissions trading schemes (ETSs), it is essential to enhance legislation and verification procedures to guarantee the integrity of carbon emissions data. China started implementing pilot ETSs in 2009 in some regions to prepare for a national scheme [42]. Accordingly, in the early debates over the ETS, there were disagreements as to whether there would be direct pilots on a sectoral or regional basis. In October 2011, China opted for a regional approach, and five cities (Beijing, Chongqing, Shanghai, Shenzhen, Tianjin) and two provinces (Guangdong, Hubei) were selected as the so-called "seven pilots" to test carbon emissions trading. The national government entrusted local authorities with designing their own ETSs based on soft national guidelines to accommodate regional circumstances.

China has a Standardization Administration that publishes general guidelines of GHG emissions accounting and reporting for industrial firms. There are detailed MRV protocols for 10 key industries [43], although monitoring and reporting of emissions are self-conducted by entities. The report is sent to a third party for verification, and the cost is covered by the local government in most of the pilots—only in Beijing and Shenzhen are firms required to pay the verifier. In Shanghai, a fourth party double-checks the verification report to guarantee its authenticity [44]. Failure to comply with MRV protocols in China is chiefly due to failing to or falsely reporting and verifying [43]. Some states (e.g., Beijing, Shanghai, Guangdong) use financial penalties to regulate firms' MRV process. Some levy 3–5$\times$ the market value of the excess CO_2 emissions while others levy a predetermined fine [44]. For transparency, it was reported [45] that for its carbon pricing system, China has developed a multitiered MRV system with 408 verification agencies, and a data-reporting system with provincial oversight that is complemented by regular public reporting requirements.

3.3.3. India

Carbon credits trading in India is shaped by the Energy Conservation (Amendment) Act of 2022, which endeavors to establish a formal carbon market in the Indian Carbon Market (ICM) [46], integrating both national and international carbon trading markets. The Act empowered the Bureau of Energy Efficiency (BEE) and the Ministry of Environment, Forest and Climate Change (MoEFCC) to develop a robust MRV framework of carbon emissions to ensure transparency and credibility of carbon credits. The Indian government has adopted a sectoral approach, since it has identified specific sectors and industries, including power generation, cement, steel, and transportation, as well as priority areas for emissions reductions.

India's federal government has framed its climate policy in the National Action Plan on Climate Change (NAPCC), outlining eight National Missions—among them sustainable agriculture—requiring specific MRV systems [47]. For instance, a 1% increase in SOC through regenerative practices could reduce the need for some 30 kg of nitrogen fertilizer in India [48], while enhancing the soil biological environment and improving soil water retention capacity. Accordingly, carbon credit incentives of INR 2000/ha per year to farmers who practice regenerative agriculture can provide farmers with additional income through private sector funds mobilization.

In the experience of Girish and Trivedi [49], farmers who follow regenerative practices can sequester 1–4 carbon credits/acre. There are also indirect benefits to farmers such as improved soil health, which can increase the soil's water-holding capacity, lower bulk density, increase water infiltration, increase nutrient availability, and reduce surface temperature.

There are some challenges to consider here, however, as accurate accounting and verification are difficult when it comes to proving additionality encompassing new practices over and above routine practice. It takes time, both for yields to improve and for the incentives to arrive. For example, it can take 12–18 months for a project to be listed and, once it is listed, another 8–12 months for funds to arrive to farmers and nonprofits [49]. Moreover, the average landholding size of an Indian farmer is just over 1 ha, and the amount of carbon credits received may not be enough for a small-scale farmer to adopt regenerative agricultural practices. In addition, because carbon trading is in its infancy in the Global South, there is currently limited awareness among farmers about it.

Nevertheless, these authors [49] advocated that farmers be made aware of the benefits of carbon credit programs, especially since the demand for carbon credits is expected to rise 15× by 2030 and 100× by 2050 [50], and worth upwards of USD 50 billion in 2030, which can cause carbon credit prices to increase substantially. However, if carbon credit programs are onboarded with farmer groups rather than individual farms, this could reduce incentives for individual farmers. Technological innovations could potentially facilitate the MRV process. If carbon credit programs are aligned with existing (natural farming, regenerative farming, organic farming) schemes, then the process could be further lubricated.

India's pathway to net zero by 2070 has demonstrated the need for digital MRV systems. According to Chaturvedi et al. [51], digital MRV systems are being piloted to track emissions and reductions for approved sectors and tag the results to a country's NDCs. For example, Ghana, Jordan, Chile, and Singapore are building end-to-end digital infrastructure. Some of the benefits include improved transparency and cost-efficiency, which could lead to savings of at least 20–30% across all stages of VCM projects [51], including MRV.

4. Discussion

The current focus of African projects on Verra's VM0042 is exemplary and warranted, since it offers opportunities for both direct sampling and modeling for setting the baseline and subsequent monitoring. Verra also requires that soil samples be collected to at least 30 cm depth and that samples be taken when there is a soil textural change [52]. It mandates that bulk density and depth are reported, as well as soil texture. The fact that Verra has moved away from purely modeled data to hybrid data collection demonstrates its recognition that more rigorous methods are needed. African countries also denote that we are not certain exactly how many projects are currently underway, as only those registered projects (CERPs) are recognized in the published literature. Kenya is illustrative of a nation where community-level initiatives are developed to make carbon farming more affordable for local farmers. Aggregating funds to the community level is an option for the Global South, as evident in Ethiopia, in the absence of government funding support.

Lessons from China include its bottom-up approach to developing emissions trading based on soft national guidelines implemented by local authorities to reflect regions. Its multitiered verification process allows for greater scrutiny, and verification cost coverage is available from most local governments. The use of fines by some states imposes further constraints on firms for failing to or falsely reporting and verifying. Having such mechanisms in place in its multitiered MRV system enhances transparency, including having data reporting overseen at the provincial level. Furthermore, having digital systems in place, combined with AI automation for processing, can improve traditional calculation approaches and address biases and inaccuracies introduced by self-reported data. Such use of manual data entry and aggregation can lead to human errors and affect data integrity and reliability.

Studies from India indicate that time is required for farmers to see yield improvements with added SOC and improved soil health, and, importantly, for the incentives to arrive to reward farmers for employing regenerative practices. Small landholders struggle with carbon trading because of their lack of awareness, as well as the required initial investments, even if they partner with nonprofits. Even though there is a caution against onboarding farmer groups, which reduces incentives for individual farmers, pooling smallholder farmers to reduce MRV costs is an effective strategy to overcome the affordability obstacle. The use of end-to-end digital infrastructure (as already deployed in Jordan [51]) can improve transparency and cost efficiency. As we have also learned from India, it is important to develop national and international infrastructure to support carbon trading.

4.1. Improvements in the Global South

Since carbon trading markets in the Global South are in formative stages, they often lack regulatory frameworks, robust technological infrastructure, and financial resources to promote participation [53]. Existing challenges impede the development of comprehensive carbon trading systems, affected by limited access to capital, insufficient institutional capacity, and inadequate policy enforcement. Therefore, targeted development efforts are needed in the Global South. These markets can be bolstered through intermediaries (brokers, exchanges, certification bodies) to bridge the gap between policy and practice and facilitate transactions, promote transparency and trust among market participants, and ensure the credibility of carbon credits through rigorous verification processes. Intermediaries also foster organizational collaborations among a diverse range of stakeholders (governments, nongovernmental organizations (NGOs), private sector entities). Intermediaries may also provide platforms and networks for carbon trading activities, helping to standardize protocols and create market mechanisms that are designed for specific regional conditions and needs. Furthermore, their efforts are crucial to address existing gaps and enhance the efficacy and credibility of carbon trading markets.

Although MRV systems are implemented to enhance transparency and ensure compliance [53], in many developing nations, missing institutional support and technical expertise represent full implementation challenges. Moreover, setting up MRV systems has associated high costs that can restrict smaller firms and underfunded projects from participating in carbon trading markets. The flexibility of cap-and-trade systems allows for adaptation to local contexts, offering opportunities for policymakers in the Global South to experiment with hybrid models, incorporating both mandatory and voluntary participation. A six-pillar reform framework has been proposed by Sasaki [54] that is based on practical tools, such as legal mechanisms to boost credit quality and stakeholder confidence, rights-based standards, AI-assisted MRV, and blockchain-enabled registries.

4.1.1. Improving SOC MRV Methods

New technologies and standardized protocols at low transaction costs can improve SOC MRV [55]. In the Global South, there are more opportunities to implement improved practices since developing countries are limited in technical capacity, data availability, and infrastructure for a robust SOC MRV [55].

By tackling practices rather than direct soil measurements, practice-based approaches that are more cost-effective are also more robust when accompanied by process-based models combined with strategic soil measurement. There needs to be, however, model calibration and continuous improvement based on field measurements to reduce uncertainties, which may limit some countries in the short term. The use of basic account approaches (e.g., IPCC-Tier 1) is a good starting point. However, recent innovations and applications of remote sensing techniques and soil databases will soon improve data availability, reduce costs, and improve accuracy in estimating SOC changes.

An Organisation for Economic Co-operation and Development (OECD) report has estimated that net soil carbon sequestration on agricultural lands could offset 4% of annual global (human-induced) GHG emissions [56]. This could make an important contribution to meeting national targets ratified in the Paris Agreement. A package of policies is needed to enhance global soil carbon stocks, including regulations to prevent the loss of soil carbon, knowledge-transfer policies, and additional incentives—the latter to address concerns regarding nonperformance of carbon stocks and reduce transaction costs. It should be noted that these authors [56] did not consider the issue of leakage, which ensures that a project does not result in increased emissions off-site. Moreover, permanence is typically defined as the maintenance of carbon stock over 100 years.

Cropland management practices are currently limited to reduced tillage, crop rotation, and cover crops, and there is still uncertainty about the spatial-temporal patterns of SOC accrual on working farms under different management practices. Although, efforts are underway to integrate data and existing knowledge (e.g., OpenTEAM, CIRCASA) and will increase our understanding of agricultural management impacts on SOC sequestration across a variety of working farms [4]. Since SOC can significantly vary over space and only slowly accumulates, it is difficult to detect change without collecting and analyzing a high density of soil samples, which is expensive and can be cost-prohibitive. For these reasons, sampling remains episodic, for example, every 5 years, and the use of process-based modeling is common [4].

Since these models will be responsible for primarily issuing credits at least in the short term, it is essential that they produce accurate and unbiased estimates of SOC sequestration. Presently, there is little evidence that existing models accurately capture SOC change at the field level across all proposed management interventions and soil–climate combinations. Only a handful of models (e.g., DayCent, DNDC, RothC, Century) have been thoroughly assessed in agricultural systems and in a variety of regions to standards required by most protocols [34]. Designing a soil sampling strategy that adequately captures spatial heterogeneity while reducing uncertainty in SOC stock estimates is important. Soil sampling details provided by published protocols may prove insufficient, depending on the challenges associated with quantifying SOC and the level of certainty demanded by credit buyers.

4.1.2. Further Considerations for Dryland Regions

Soils differ around the world, making the standardization of SOC sampling problematic. Nontropical dryland regions in the Global South mainly constitute aridisols and entisols, though other soils may be found (e.g., alfisols, mollisols in grasslands, vertisols). These soils are shallow and their profiles tend to be less developed (e.g., entisols, aridisols). They can accumulate salts, carbonates (lime), and gypsum due to mineral weathering and evaporation. These soils have limited vegetation growth and slow decomposition rates that contribute to low soil organic matter (SOM) content. There is also low biological activity, such as burrowing organisms, which could reduce soil mixing. Importantly, these soils tend to have poor water retention due to their coarse to medium texture, and there may appear surface soil crusts that impede water infiltration [57].

The ramifications of dryland soils for SOC MRV protocols are evident, especially for monitoring through direct measurements. Maintaining a global standard of sampling depth is difficult, since these soils are less horizonated in profile than in other climate regions. Sampling at a depth of 30 cm, for example, would represent different soil horizons in these soils than in more stratified soils. It should be noted that soil texture changes with depth as horizons change, as does the bulk density. Samples from these soils would be less heterogeneous with depth (than horizonated soils), questioning whether a depth of 60 cm (cf. [19]) would be necessary. Furthermore, volumes of collected soil cores could vary depending on the instrument used for extraction (e.g., Oakfield or Dutch augers). Extracting a standard weight of dry soil (e.g., ESM after [18]) may better maintain comparability between sampled sites. Since bulk density measurements (g/cm^3) are typically required for monitoring, then extracting a known volume of (oven-dried) soil is required anyway.

These soils can develop soil crusts, which can reduce the surface porosity and affect the bulk density [57]. If biological crusts (biocrusts) are present, these could locally augment SOM. In other words, crusted soils are vertically heterogeneous, and accounting for this spatial variability needs consideration for arid lands. The biogeochemical properties of these soils (e.g., salt content) affect biological growth as well as organisms evident in (non-tropical) dryland soils. Planting deeply rooted crops that are heat, dryness, and salt-tolerant would be ideal, especially if they have C4 pathways that minimize photorespiration.

4.2. Contributions

This review contributes to the literature on VCM in carbon trading, specifically on SOC MRV protocols and their application in nontropical dryland regions of the Global South. Egypt is considered in-depth as a case study in the MENA region. To answer the research question (Is there a case for SOC MRV protocols to be adopted in nontropical dryland nations for carbon trading?), it is necessary to examine the challenges posed by SOC MRV protocols in this region. These challenges are augmented in the Global South, where the VCM is relatively new and depends on certification programs (e.g., Verra in African countries). There are further challenges targeted in the MENA region, such as the greater occurrence of carbonates at depth and soil development in dryland soils, which question testing with horizon change in the soil profile. These could considerably add to field costs incurred by Tier-3 measurements. As for the 30 cm depth standard, this can be justified in the Global North by the depth of mechanized machinery (e.g., moldboard plowing) that goes up to 30 cm depth, encompassing the topsoil, which is most connected in profile to management practice.

The design principles for MRV protocols in arid regions could incorporate model-assisted approaches to accommodate the dryland soils found in this region. Sampling monitoring cycles in this region could be constrained if retained in a 5-year period. It takes time for SOC to accumulate in soils, and particularly in dryland soils due to high temperatures, salinity, and low moisture affecting decomposition. For example, areas with shallow groundwater will accumulate more SOC stock than elsewhere in this region.

To finally answer the review research question affirmatively, one needs to additionally consider that even though arid soils are carbon-depleted in this region, because agriculture is a major industry in the developing countries of the Global South, there are opportunities here for conjoint economic-environmental benefits. In Egypt, for example, the AFOLU sector accounts for nearly 11% of its total inventory [39].

The unique contributions of this review include practical insights from regional cases used to inform the Egyptian case study. Additionally, the MRV adaptation framework for arid regions allows for consideration of measurement issues in dryland soils. These issues are less problematic in Verra's methodological standard (e.g., Verra's VM0042), which is recommended as a verification standard. Nevertheless, measurement issues need consideration as part of the monitoring process. Such issues as depth, texture, and bulk density influence SOC MRV methods and their comparability across different soil types. Inputs are required from a diversity of soil specialists to inform both ground-based measurements and modeling approaches.

By considering 53 publications, including reports from governments and NGOs, this review accesses nonacademic (policy) information that is both topically relevant and suitable as well as practical. Based on these sources and regional lessons learned, it is evident that a disjuncture exists between practice (by farmers) and governments in terms of generated awareness and access for small landholder farmers. A further disjuncture is evident at the national–international level, which could become obvious with the adoption of digital technology. Automating the process (building end-to-end digital infrastructure, as already evident for MENA nations such as Jordan [51]) is beneficial from the end-user (farmer) perspective, since it removes human-imposed limitations that are particularly restrictive in the Global South.

4.2.1. Economic Viability of Carbon Projects in Arid Regions

The barriers to policy implementation need to be highlighted. An important one is the limited participation potential for smallholder farmers due to the economic viability of small farms in carbon trading. However, as already implemented elsewhere (e.g., in African countries like Kenya; India), these farmers can develop community partnerships to amalgamate their acreage and turn it into a community investment. There are also gaps in technical capacity in the Global South, which can be filled through collaborations with nonprofits in the Global North or by international organizations such as World Vision.

There are added constraints due to technology and the need for technical knowledge, especially as MRV protocols head toward improved integration and digital access. Specific technologies (e.g., AI-optimized sampling point layouts) will need technical collaborations with participating farms; for example, nonprofits that are trained using modernized protocols. Policy instruments are another option for broadening participation, as carbon tax revenue reinvestment is used to reduce MRV costs.

To revisit the research question guiding this systematic review, as to whether there is a case for using SOC MRV protocols in nontropical dryland nations for carbon trading, the simple answer is "yes." First, countries in the Global South, including Egypt and the MENA region at large, have extensive land used for agriculture. Even though SOC content may be low in surface soils in this region, much of the land is farmed, and there is great potential for working in conservation agricultural techniques that are sustainable and can contribute to Sustainable Land Management (SLM). Second, through community efforts, it is possible to amalgamate areas where there are small farms (as already being executed elsewhere in African countries, India). Third, collaborations with experts, including nonprofits that have technical knowledge, could support such endeavors.

The design principles for MRV protocols in arid regions could include prioritizing shallow groundwater, using model-assisted approaches, and deploying extended monitoring cycles. There is already much pressure on aquifers for irrigation in dryland regions using shallow groundwater resources, including some traditional techniques for capturing and storing rainwater at different scales. Model-assisted approaches require reducing the costs associated with direct sampling. Perhaps enough baseline data could be acquired through field testing, and follow-ups could be reduced—although this may be constrained by the need for "ground-truthing" in the verification requirements across different programs. Whether extended monitoring programs can be executed likewise depends on the requirements of the verification program.

4.2.2. Recommendations and Future Directions

The economic viability of carbon projects in arid regions needs assessment from the perspective of MRV methods.

(1) Adopting AI technologies to automate the process to a fully integrated system requires building an end-to-end digital infrastructure. Investments are already being made by Verra with its registry digitalization that uses built-in algorithms to automate calculations. Such developments establish Verra as the leading GHG crediting program (https://verra.org/programs/verified-carbon-standard/, accessed on 9 July 2025).
(2) Other suggestions are AI-optimized sampling point layouts, AI-automated and online accessible data entry (besides project registration), and enhanced reporting standardization.
(3) Policy tools could be further deployed, such as carbon tax revenue reinvestment, to reduce MRV costs.

There is potential to develop nonintrusive/remote methods for soil measurements. For example, integrating remote sensing with AI and using multisource data fusion. Machine learning has the potential to improve prediction accuracy and assist in modeling soil biogeochemical dynamics.

5. Conclusions

Nontropical dryland nations in the Global South, such as Egypt and other countries in the MENA region, need to consider the challenges when employing SOC MRV protocols in the VCM. These challenges will influence the design of pilot studies, baseline setting, and project implementation. Arid soils are influenced by locational challenges, such as crusting and salinization, that have implications for soil structure and the bulk density as well as biogeochemistry, which have the potential to impact SOC measurements. These issues are linked with the arid environment in which these soils develop. The MRV literature needs to incorporate lessons from soils specifically for arid climate regions. It is also important to consider soil characteristics (information from soil science), like texture, since this influences the ability of soils to capture and store carbon in pore spaces while affecting drainage and water retention. Integrating considerations linked to a knowledge of soils alongside works addressing MRV protocols allows for a more holistic, evidence-based approach. Further integration can also occur between public and private initiatives and their regulatory frameworks at national and international levels of governance.

To conclude, the key findings and contributions of this review are as follows:

(1) Most of the challenges for MRV protocols are in the monitoring phase of MRV protocols, and to a lesser extent, in reporting and verification. These challenges stem from a "one-size-fits-all" approach to measurements evident in current monitoring methods. Greater attention needs to be directed toward an international protocol that considers the global climate and its impact on the distribution of soils with different SOC content.

(2) As demonstrated by the case for Egypt, although there are national-international attempts at addressing agriculture (and agricultural soils) within climate change strategies, VCMs need better integration into private-public legislative frameworks that help increase awareness among end-users and provide initial funding support to allow smallholder farmers to participate alongside large (commercial) farms.

(3) MRV protocols are currently executed with assistance from nonprofits, and in some cases aggregation to the community level is required to make the process feasible. An end-to-end, accessible digital framework, with project developers set in motion to guide end-users through the entire process, may encourage more participation, especially in developing countries where carbon trading has only recently been introduced. Farmers turn to carbon programs like Verra because of its well-defined methodology and the direction it provides to end users.

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Abbreviations

The following abbreviations are used in this manuscript:

AFOLU	Agriculture, Forestry, and Other Land Use
BEE	Bureau of Energy Efficiency
BUR	Biennial Update Report
CDR	Carbon dioxide removal
CERC	Carbon Emission Reduction Certificate
CERP	Carbon Emission Reduction Project
CH_4	Methane
CO_2	Carbon dioxide
COMET	CarbOn Management Evaluation Tool
COP26	The 26th United Nations Climate Change Conference

CWANA	Central and West Asia and North Africa
DNDC	DeNitrification-DeComposition
EGX	Egyptian Stock Exchange
ESM	Equivalent soil mass calculation
ETF	Enhanced Transparency Framework
ETS	Emissions trading scheme
FAO	Food and Agriculture Organization
FD	Fixed-depth
FRA	Financial Regulatory Authority
GCC	Gulf Cooperation Council
GHG	Greenhouse gas
GPS	Global Positioning System
ICM	Indian Carbon Market
ICROA	International Carbon Reduction and Offset Alliance
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life cycle assessment
MENA	Middle East and North Africa region
MIR	Mid infrared
MoEFCC	Ministry of Environment, Forest and Climate Change
MRV	Monitoring, reporting, and verification
NAPCC	National Action Plan on Climate Change
NCCS	National Climate Change Strategy
NDC	Nationally Determined Contribution
NGOs	Nongovernmental organization
N2O	Nitrous oxide
NRCS	Natural Resources Conservation Service
NRT	Northern Rangeland Trust
OECD	Organisation for Economic Co-operation and Development
PEG	Private environmental governance
RMSE	Root mean square error
SADS	Sustainable Agricultural Development Strategy
SAIL	Sustainable Agriculture Investments and Livelihoods
SLM	Sustainable Land Management
SOC	Soil organic carbon
SOM	Soil organic matter
UAV	Unmanned aerial vehicle
UNFCCC	United Nations Framework Convention on Climate Change
USDA	United States Department of Agriculture
VCM	Voluntary Carbon Market
VCS	Verified Carbon Standard

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