Carbon Farming in Contemporary Agriculture: Scientific Foundations & Digital Infrastructures

Ilias Seitanidis, Gina Athanasiou, Panagiotis Athanasoulis, Georgios Varras, Theodore Zahariadis

Abstract—**Carbon farming is increasingly discussed as a land-management approach that can connect climate mitigation with soil restoration and farm resilience. In European and international policy debates, the term generally refers to practices that enhance carbon sequestration in soils and biomass and, in some cases, reduce greenhouse gas emissions from agricultural land. This paper analyses carbon farming as both a biophysical process and a policy instrument, with additional attention to the digital infrastructures required for operational monitoring and thematic product delivery. It reviews the scientific basis of soil organic carbon accumulation, analyses the principal practices associated with carbon farming, and evaluates their environmental co-benefits and implementation constraints. Particular attention is given to measurement, reporting, and verification challenges, including additionality, permanence, reversal risk, and the cost of monitoring soil carbon change. We argue that carbon farming should not be reduced to a narrow offset mechanism. Instead, it may improve soil health, water retention, biodiversity, and long-term resilience while contributing, within clear limits, to climate goals. Carbon farming can become a credible pillar of sustainable agriculture only when it is grounded in conservative accounting, fair incentives for farmers, and robust digital as well as policy architectures that reward ecological integrity rather than symbolic carbon claims.**

Index Terms—**Carbon Farming, Digital Infrastructure, Earth Observation, Interoperability, Measurement, Reporting, and Verification (MRV), soil organic carbon.**

I. INTRODUCTION

Agriculture occupies a central position in climate policy because it is simultaneously a source of greenhouse gas emissions, a sector highly exposed to climate impacts, and a potential sink for atmospheric carbon. According to the Food and Agriculture Organization of the United Nations [1], global agrifood systems emitted 16.2 Gt CO2eq in 2022, representing 29.7% of total anthropogenic emissions. These emissions arise from farm-gate crop and livestock activities, land-use change, and pre- and post-production processes across food supply chains. The climate challenge for agriculture is therefore not limited to reducing direct field emissions; it also requires a broader reconsideration of how agricultural landscapes regulate carbon, water, biodiversity, and ecosystem stability.

Against this background, carbon farming has gained attention as a practical pathway for integrating climate mitigation into everyday land management. The European Commission defines carbon farming as climate-friendly practices implemented by farmers and foresters to enhance carbon sequestration in forests and soils and to reduce greenhouse gas emissions from soils [2]. This definition is analytically important because it presents carbon farming as more than a single agronomic technique. It is simultaneously a management strategy, a monitoring challenge, and a policy instrument intended to reward measurable environmental performance.

The rise of carbon farming also reflects a broader shift in how agricultural sustainability is understood. Conventional approaches are often focused on productivity, nutrient management, or conservation as partially separate domains. Carbon farming, by contrast, links these domains through the carbon cycle. Soil organic matter, biomass accumulation, microbial activity, nutrient retention, infiltration capacity, and resilience to drought are all connected to carbon dynamics. For this reason, carbon farming is frequently discussed alongside regenerative agriculture, agroecology, and climate-smart agriculture, even though it retains a distinct emphasis on quantifiable mitigation outcomes.

This paper analyses carbon farming through an integrated biophysical, economic, policy, and operational perspective. It first clarifies the concept and its scientific foundations, then reviews the principal practices associated with carbon farming, examines the main constraints on implementation, including verification, governance, and economic feasibility, and finally discusses the role of digital infrastructures in making carbon-farming workflows operational and auditable. The central argument is that carbon farming has substantial value, but only when it is embedded in robust scientific assessment and understood as part of a wider transformation of agricultural systems rather than as a simplified marketable offset.

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II. CARBON FARMING AS A SCIENTIFIC AND POLICY CONCEPT

At first glance, carbon farming appears conceptually straightforward: management changes that increase carbon storage in soils and biomass, or reduce field-level emissions, can improve the climate performance of agricultural land. In practice, however, the concept is more heterogeneous than this formulation suggests. In European policy discourse, carbon farming includes both sequestration activities and soil-related emission reductions, such as improved fertilizer efficiency or peatland rewetting [2]. In other words, carbon farming is not limited to the removal of carbon dioxide from the atmosphere; it also encompasses management changes that reduce nitrous oxide or carbon dioxide losses from agricultural land.

A second conceptual point concerns scale. Carbon farming is often communicated at the field or farm scale, because that is the level at which management changes are implemented. However, the significance of carbon farming must also be judged against the wider emissions profile of agrifood systems. FAO data show that nearly half of agrifood emissions in 2022 came from crop and livestock activities within the farm gate, with the rest deriving from land-use change and supply-chain processes [1]. This means that carbon farming can address only part of the agrifood climate problem. It is therefore best interpreted as a necessary but insufficient component of agrifood decarbonization.

The changing share of agrifood emissions in the global total further illustrates this point. Although agrifood systems emissions rose by 10% between 2000 and 2022, their share of total anthropogenic emissions fell from 38.0% to 29.7% because emissions from the rest of the economy grew even faster [1]. Carbon farming should therefore not be romanticized as a stand-alone solution to agricultural climate impacts. Rather, it is one element within a broader mitigation portfolio that must also include dietary transitions, reductions in food loss and waste, cleaner energy use, and emissions control across supply chains.

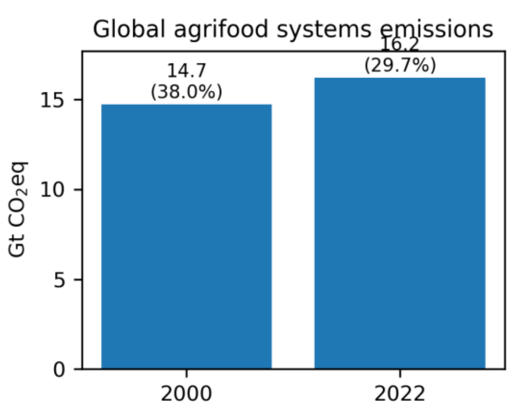

Fig. 1. Global agrifood emissions in 2000 and 2022
Note. Bar labels report total agrifood systems emissions and the corresponding share of total anthropogenic emissions. The 2000 total (14.7 Gt CO2eq) is derived from FAO's statement that 2022 emissions were 10% higher than in 2000. Data from FAO [1].

III. BIOPHYSICAL FOUNDATIONS AND PRACTICE PORTFOLIO

The scientific basis of carbon farming is rooted in soil organic carbon dynamics and biomass accumulation. Carbon enters agricultural soils primarily through plant residues, root exudates, and organic amendments. Then, it is stabilized through interactions with minerals, aggregates, and microbial transformations, but it is also continuously lost through decomposition, erosion, and disturbance. Management therefore influences whether a field behaves more like a carbon source or a carbon sink. Tillage, bare fallows, residue removal, and poorly managed organic soils tend to accelerate losses, whereas cover crops, reduced disturbance, diversified rotations, residue retention, and perennial vegetation can improve carbon retention over time.

The practice portfolio typically associated with carbon farming is diverse. In arable systems, commonly cited measures include catch crops or cover crops, conservation tillage, longer and more diverse rotations, the incorporation of compost or manure, and precision fertilizer management. In grazing systems, improved pasture management and adaptive stocking can increase belowground carbon inputs and reduce degradation. In perennial systems, mulching, inter-row vegetation cover, agroforestry, and hedgerow integration can increase both aboveground and belowground carbon stocks. The European Commission explicitly lists rewetting of peatlands and wetlands, agroforestry, soil protection measures such as cover crops and conservation tillage, afforestation, and improved fertilizer-use efficiency among the main examples of carbon farming [2].

From a climate perspective, these practices matter for different reasons. Some primarily increase carbon sequestration in soils or biomass, while others mainly reduce emissions that would otherwise occur. Rewetting peatlands, for example, reduces carbon oxidation from drained organic soils; agroforestry enhances longer-term biomass storage; improved fertilizer efficiency lowers nitrous oxide emissions; and cover crops help maintain living roots and reduce erosion while potentially increasing soil organic matter. Carbon farming is thus not a single biophysical pathway but a set of mechanisms operating through carbon inputs, carbon retention, and avoided losses.

At the same time, the sequestration potential of these practices is strongly context dependent. Soil type, climate, management history, crop system, and the duration of implementation all shape outcomes. The Intergovernmental Panel on Climate Change [3] and synthesis work by Smith et al. [4] both emphasize that land-management practices should be evaluated not only for mitigation potential but also for adaptation benefits, land competition, and co-benefits. This is a crucial qualification. A practice that performs well in one agroecological region may produce smaller gains elsewhere, and some gains may diminish as soils approach a new equilibrium.

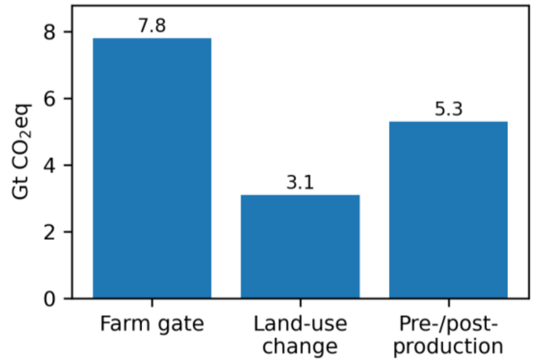

Fig. 2. Composition of global agrifood systems emissions in 2022
Note. Values represent farm-gate emissions, land-use change emissions, and pre-/post-production emissions within global agrifood systems. Data from FAO [1].

IV. CO-BENEFITS, RESILIENCE, AND TRADE-OFFS

One reason carbon farming has become so influential is that its benefits extend beyond carbon accounting. Increases in soil organic matter often improve aggregate stability, infiltration, water-holding capacity, and nutrient cycling. These changes can strengthen resilience to drought, reduce erosion, and support more stable yields under climatic stress. For many farmers, such agronomic and hydrological benefits may be more tangible in the short term than the climate effect itself. Carbon farming is therefore best justified not as a purely atmospheric intervention, but as a strategy for improving the ecological functioning of agricultural systems.

This broader perspective is supported by comparative evidence. Smith et al. [4] found that several land-management options can co-deliver mitigation, adaptation, reduced land degradation, and food-security benefits when implemented under appropriate conditions. The significance of this finding lies in its rejection of a narrow trade-off framework. Carbon-oriented practices do not necessarily undermine productive agriculture; in many cases they strengthen the resource base on which production depends. However, the same review also warns that not all practices are universally beneficial and that scale matters, particularly where land competition or ecological trade-offs are involved.

Emerging social-science research adds another layer to this picture. Studies of European front-runner farmers show that carbon farming is rarely implemented as a set of isolated interventions [5]. Instead, farmers assemble bundles of practices, revise them experimentally, and negotiate trade-offs over time. This observation is important because it challenges the administrative tendency to treat carbon farming as a checklist of discrete actions. In practice, carbon farming is embedded in the overall management logic of the farm. Incentive systems that reward only individual practices may therefore fail to capture the systemic character of on-farm ecological change.

These considerations are especially relevant in drought-prone and erosion-sensitive environments, where soil cover, organic matter, and woody integration can influence not only carbon sequestration but also thermal buffering and water regulation. In such contexts, carbon farming functions as a resilience strategy as much as a mitigation strategy. Its value lies not merely in the tonnes of carbon counted, but in the restoration of ecological processes that allow farming systems to remain viable under worsening climatic pressures.

V. MEASUREMENT, REPORTING, VERIFICATION, AND INTEGRITY CHALLENGES

The main scientific challenge of carbon farming is not the identification of promising practices, but the reliable quantification of their effects across heterogeneous soils, climates, and management histories. Soil carbon changes are often slow, spatially variable, and expensive to detect. Realizing the mitigation potential of soil carbon sequestration depends on credible systems to measure, report, and verify change, yet these systems remain technically demanding because of repeat soil sampling, model calibration, and uncertainty management [6]. This challenge becomes particularly important when carbon claims are linked to financial rewards or tradable credits.

The problem becomes more complex because carbon farming involves both biophysical uncertainty and accounting uncertainty. Weather variability can mask the effect of management changes. Baseline conditions may be poorly documented. Different sampling depths or laboratory methods can produce different results. In addition, increases in soil carbon usually occur gradually and may plateau over time. For these reasons, high-integrity carbon farming requires conservative accounting rules, transparent uncertainty treatment, and hybrid monitoring approaches that combine field measurements, modeling, and digital activity data.

Three concepts are central here: additionality, permanence, and reversal risk. Additionality asks whether the credited benefit would have happened in the absence of the intervention. Permanence asks how long the stored carbon remains out of the atmosphere. Reversal risk addresses the possibility that stored carbon may later be lost because of tillage, drought, fire, land-use change, or contractual non-compliance. The Joint Research Centre has recently highlighted reversal risk as a structural issue for carbon farming projects under the EU framework, particularly where biological storage is temporary and management dependent [7]. These challenges do not invalidate carbon farming, but they do mean that soil-based carbon claims are inherently different from permanent geological storage.

For these reasons, carbon farming should not be treated as a frictionless offset commodity. A scientifically serious carbon-farming agenda must accept that some benefits can be estimated only probabilistically, that monitoring is costly, and that short-term claims may overstate long-term climate value. In this respect, carbon farming is better understood as a managed environmental service that depends on durable stewardship and careful governance.

VI. ECONOMICS, GOVERNANCE, AND THE EMERGING EUROPEAN FRAMEWORK

The economic promise of carbon farming lies in the possibility that farmers can be compensated for ecological services that are rarely rewarded by conventional agricultural markets. The European Commission's early policy framing described carbon farming as a green business model in which land managers may receive result-based payments for improved practices or for achieved mitigation outcomes [8]. In principle, this could diversify farm income and help support the transition toward more resilient systems. In practice, however, the distribution of costs, risks, and administrative burdens is decisive.

Farmers face several potential barriers to adoption. Transitioning to new practices may require learning, equipment changes, altered labour patterns, or short-term yield uncertainty. Monitoring and certification can impose transaction costs. Long-duration contracts may create hesitancy if future weather or market conditions are uncertain. If liability for reversals is pushed heavily onto land managers, participation may become unattractive. This is why the institutional design of carbon farming schemes matters as much as the agronomy. Fair payment levels, risk-sharing mechanisms, advisory support, and transparent rules are essential conditions of uptake.

At the governance level, the European Union has moved rapidly to formalize the field. Regulation (EU) 2024/3012 established a Union certification framework for permanent carbon removals, carbon farming, and carbon storage in products [9]. The European Commission describes this as the first EU-wide voluntary certification framework and notes that the Regulation is intended to set quality criteria and monitoring and reporting processes while reducing greenwashing [2]. The Commission has also been developing specific carbon-farming methodologies for mineral soils, peatland rewetting, and afforestation, with further work expected in 2026.

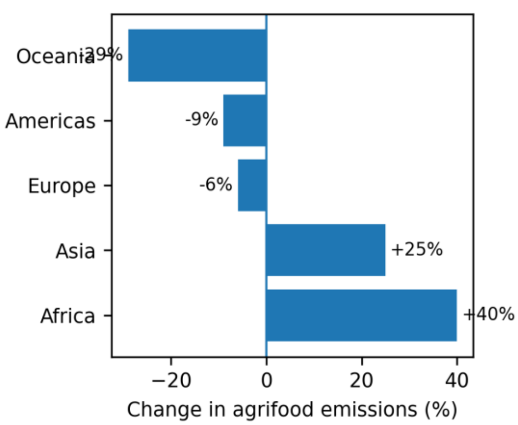

Fig. 3. Regional change in agrifood emissions between 2000 and 2022. *Note. Positive values indicate growth in emissions relative to 2000; negative values indicate decline. Data from FAO (2024).*

This regulatory shift matters because it moves carbon farming beyond a largely aspirational policy discourse and into a more formal system of certification, methodological standardization, and institutional oversight. Yet the credibility of the framework will depend on whether it avoids two opposite errors. One error would be excessive simplification: rewarding easily counted actions without securing real climate integrity. The other would be excessive bureaucratic complexity: creating verification systems so burdensome that only a small fraction of farms can participate. Effective governance must therefore strike a balance between scientific robustness and practical feasibility.

Most importantly, carbon farming policy should complement, not displace, absolute emissions reductions in agriculture and food systems. Carbon sequestration on farms cannot substitute for reducing fossil-energy use, methane emissions, supply-chain emissions, or land conversion pressures. The most defensible role for carbon farming is therefore supportive and regenerative: it can strengthen soil health, restore ecological functions, and provide bounded climate benefits, but it should not be used to justify continued emissions elsewhere without scrutiny.

VII. DIGITAL INFRASTRUCTURES FOR OPERATIONAL CARBON FARMING

The scientific and policy literature on carbon farming often concentrates on practices, incentives, and accounting rules, but the operationalization of these systems increasingly depends on digital infrastructures able to integrate heterogeneous data streams. This requirement is especially clear in monitoring settings where soil observations, remote sensing products, telemetry, laboratory analyses, and model outputs must be aligned into auditable workflows. In this respect, carbon farming is not only an agronomic transition but also an information-systems challenge.

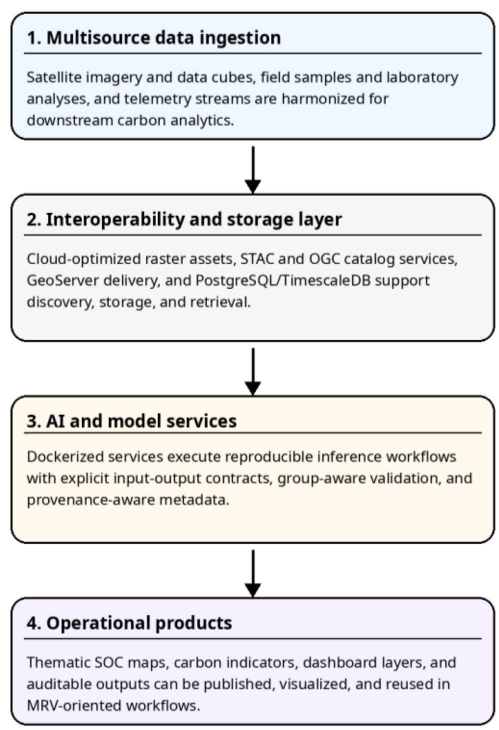

Fig. 4. Original schematic of an operational carbon-farming pipeline informed by the GLE platform architecture and AI integration workflow *Note. The schematic is an original synthesis prepared for this manuscript based on the textual descriptions in [10] and [11]; no figure from the source deliverables has been reused.*

The first Greek Living Earth platform release provides an instructive example of such architecture. Its functional modular design organizes user and access management, telemetry ingestion, satellite-image management through a data cube, field and chemical analysis management, and dashboard-based visualization within a single environment. The platform adopts a catalog-first approach in which raster products are managed as cloud-native assets and exposed through standards such as STAC API, OGC API-Records, OGC CSW, OpenSearch, and GeoServer services, while field and telemetry data are handled through PostgreSQL/ TimescaleDB and structured APIs [10].

The companion AI integration deliverable makes explicit how analytical models can move from research code to operational services. It frames AI components as Dockerized services with reproducible runtimes, defined input-output contracts, and publishable thematic outputs. Just as importantly, it emphasizes group-aware validation, bootstrap cross-validation, ensemble logic, and minimum provenance and metadata requirements so that generated products are technically reproducible and traceable within the broader platform [11]. For soil-carbon-related applications, these design principles are directly relevant to the production of SOC maps and other indicators used in carbon-farming assessment.

These project-level design choices illustrate a wider point for the carbon farming literature: credible Measurement, Reporting, and Verification (MRV) cannot rest on field measurements alone. It also requires interoperable architectures capable of linking acquisition, preprocessing, model execution, metadata, visualization, and retrieval. Where such infrastructures are absent, carbon-farming claims are more difficult to audit, update, or scale. Operational carbon farming therefore depends not only on better land management, but also on robust digital systems that can support traceability, uncertainty-aware analytics, and consistent publication of thematic products [10], [11].

VIII. CONCLUSION

Carbon farming has become an influential concept in contemporary agricultural policy because it connects climate mitigation to the material condition of agricultural land. Its scientific basis is clear: management practices affect soil organic carbon, biomass accumulation, and soil-related greenhouse gas emissions. Its practical benefits can also be substantial, particularly where improved soil cover, organic matter, and landscape complexity strengthen resilience to drought, erosion, and ecological degradation. In this sense, carbon farming offers a meaningful pathway for reconnecting agricultural productivity with ecological stewardship.

Nevertheless, the concept must be handled with precision. Carbon gains are difficult to measure, often reversible, and strongly dependent on local conditions. Some practices produce multiple benefits, but not all do so equally or permanently. A credible carbon-farming strategy must therefore be conservative in its claims and ambitious in its ecological vision. It should prioritize long-term land restoration, farmer support, and transparent monitoring over simplified carbon narratives.

The most defensible future for carbon farming is not as a speculative market abstraction, but as one component of a broader transition toward ecologically resilient agricultural systems. When linked to sound agronomy, fair incentives, rigorous governance, and interoperable digital infrastructures, carbon farming can help agriculture contribute to climate goals while improving the resilience and quality of rural landscapes. Carbon is the entry point, but the deeper objective is the renewal of agricultural systems within planetary boundaries through practices and monitoring systems that are both scientifically credible and operationally robust.

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