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Executive Summary

Scope of this document

This ORCaSa deliverable D4.4 is closely linked to the [ORCaSa deliverable D4.2](#), which focuses on the Monitoring, Reporting and Verification (MRV) of soil organic carbon (SOC) changes for arable land. This deliverable completes the deliverable on MRV SOC changes on cropland in diverse directions ([Deliverable 4.2](#)), aiming to end up with complete recommendations on SOC change MRV frameworks for multi-ecosystems, including leakages and focusing on Monitoring.

Firstly, the analyses are completed in term of land use type by adding grassland and rangeland, as well as forests, using the same framework as setup in deliverable D4.2, focusing similarly on the Monitoring, Reporting and Verification (MRV) of Soil Organic Carbon (SOC) changes. The scope is enlarged on another direction, by also analysing SOC change MRV for land uses change from one type of land use to another. Lastly, recommendations on transfers and leakage complete the picture by reviewing possible unintended consequences of MRV focused on SOC. These transfers and leakages concern GHG emissions change, carbon transfers, production change and distant SOC change allowing to compensate for the change in production, input change, and the design of MRV systems themselves.

Non-forested non-agricultural land uses are only partially in the scope of the deliverable, mainly through change in SOC associated to land use change. Agroforestry and silvopastoralism are not excluded and some considerations specific of these land uses are provided, but there is no in-depth analysis of these systems.

Target audience

The target audience and intended use of this deliverable are wide: anyone who has an interest in quantifying or verifying SOC stock changes may find this document useful. Indeed, a set of methods and tools for monitoring and verifying SOC stock changes in various MRV contexts are described, analysed and propositions for methodological improvements are made, a complete discussion of SOC changes and leakages are provided. Therefore, this document will be of interest to individual farmers, agricultural advisers, land managers, carbon credit certifiers, MRV tool developers, researchers, those undertaking life cycle assessment studies, environmental consultants, conservation organizations, agribusiness professionals, policy makers or regulators at local, regional, national or international scales.

Methodology and key results

This deliverable is the result of a literature review on the different methodologies, tools and building blocks for measuring and verifying SOC stocks and stock changes or for modelling SOC stocks and stock changes for different MRV contexts, including a review of existing MRV tools. It uses the same conceptual framework and methodology than deliverable D4.2 for the analysis of grassland and forest SOC MRV.

The analysis of SOC MRV changes associated to land-use change is also based a review of existing literature and MRV frameworks. **The recommendations focus on the design rather than on the operationalization of MRV systems.** Leakages and transfers analysis and recommendations are based on a literature review, but also on a critical assessment of possible leakages based on other GHG emissions reduction policy analysis, in particular biofuel policies, the literature focused on leakages in relation to SOC change being sparse.

Grasslands and rangelands and forest SOC MRV review shows that the interest for SOC MRV for those land uses is more recent than for cropland. The type of tools that can be used for monitoring of SOC change are similar to those for croplands. However, many differences exist, requiring adapted approaches for different categories of land use. Taking into account the possibility of land use change in SOC monitoring does not change importantly the monitoring methods, but requires more thinking on the design of MRV systems to avoid getting credit for accumulating carbon that was released before. Incorporating leakages and transfers into the design of SOC MRV systems is important for their credibility and ultimate effect. All the MRV systems incorporate some check on GHG emissions. Other types of leakages are only considered in some MRV frameworks. Taking into account the effect of local production change on distant SOC change, which compensates for the local change in production under a fixed demand assumption should influence the design of MRV frameworks, with explicit representation of trade-offs between local changes in SOC and changes elsewhere triggered by local changes.

Research and technical implications

Monitoring SOC in forest ecosystems differs markedly from cropland due to slower dynamics, pluri-annual storage of carbon in the biomass, importance of litter, deeper carbon pools, and limited direct management interventions. Grassland and rangelands are intermediary in term of dynamics, and are also characterized by deeper carbon pools. The importance of livestock management for SOC change and the diversity of management, including mobile herds and communal grasslands requires important adaptations to SOC monitoring compared to croplands. The models used for SOC dynamics representation tend to be similar to those used for croplands, but require specific calibration. Integration of SOC dynamics in decision support tools is less advanced for forests than for croplands. For grassland and rangelands, the situation is intermediary, decision support tools with SOC dynamics exist, but their deployment outside of the research community is not already effective. Integrated processing chains for SOC MRV based on measurements in specific plots, modelling and earth observation, adapted to forests and grassland are being built and hold promises for Tier 2/3 monitoring, but are not ready yet. Established data infrastructures are in functioning, especially for forest, but would need to be modified for SOC change monitoring. Tropical forests and grasslands present challenging conditions for monitoring, because of specific practices, such as transhumant pastoral livestock rearing, recently changing land uses, lack of data and small-scale heterogeneity. Participatory approaches at the local level could be relevant in these contexts.

SOC change associated to land use change and diverse leakages and transfers, through input, change in production, or change in GHG emissions are critical for credible and efficient MRV, and implemented in some MRV frameworks. Despite the importance of these subjects there is less research discussing

and evaluating how this should change the design and operation of SOC monitoring. This is all the more important that these effects could even lead to a reversal in term of overall effect of local SOC change project appearing efficient.

Policy implications

A first result of the reviews is that differences between croplands and other land uses, forests and grassland and rangelands require a profound adaptation of MRV tools, even though the overall conceptual frameworks can be similar. In general, the specificity of forests and grasslands corresponds to increased challenges for SOC monitoring, because of carbon dynamics that occurs over longer timescales and heterogeneous practices that may range from very light management in extensive grasslands and semi-natural forests to intensive management in sown and fertilized pastures and in tree plantations. Operationalization of decision support tools is constantly improving, but is less advanced than for cropland. Carbon stored in grasslands and forests is in general more stable than in croplands, but bears more risks of losing large quantities of accumulated carbon because of land use change or disturbances. Differences between production oriented large and homogeneous systems mainly found in temperate climates and other systems are important for forests and even more for rangelands, and would require important adaptation of SOC MRV, with local participatory systems being a possible option.

Taking into account land use change in MRV systems is important and requires going into the direction of multi-ecosystem MRV frameworks. In addition to permanence, accuracy and additionality, it is crucial to take into account leakages and transfers in the design of MRV systems, as the magnitude of the effects can be similar to the locally accumulated carbon in SOC, potentially leading to a reversal of the overall effect of the intervention. Accounting for displacement of production tend to favour higher yielding systems in relation to the SOC carbon they can accumulate, but bears the risk of increased pollution, therefore provision for other environmental impacts than GHG emissions reductions and SOC increase should be incorporated in MRV frameworks to avoid pollution displacement and other negative environmental impacts.

Main characteristics of SOC MRV across Grasslands, Rangelands & Forests

NB: Of course, the physical and chemical characteristics are essential, but as is a generic driver it is not specifically mentioned in the table.

Dimension	Grasslands	Rangelands	Forests
Spatial boundaries	Clear, plot-level; easy to map	Diffuse; communal lands; mobility corridors	Clear but large; often mapped through forest inventories and remote sensing
SOC change rate	Medium (5–10 years)	Slow (10–20+ years)	Slow (10–20+ years)
Main drivers of SOC	Management intensity, grazing regime, fertilization, species composition	Climate variability, grazing pressure, mobility patterns, land-use legacy	Climate, soil, disturbance regimes, litterfall and root dynamics, species composition, stand age for even-age forest, management
MRV for SOC feasibility	High	Low–medium	Medium
Best MRV scale	Farm / plot	Landscape / territory	Stand / concession / landscape ; jurisdictional scale suitable for Tier 2
Main MRV tools	Farm records, NDVI/EVI, stratified sampling	Remote sensing of degradation, participatory monitoring, long-term sampling	SOC sampling, Remote sensing (MS, LiDAR, radar), forest inventories, Tier 3 SOC models, disturbance datasets
Data availability	Generally good	Often limited or fragmented	Variable; good vegetation and disturbance data globally; soil data sparse, shallow and limited deep-soil and chronosquence data. Good availability where REDD+ exists (but limited integration of SOC)
Key challenges	Ensuring permanence;	Heterogeneity, herd mobility, climatic extremes	Slow SOC dynamics; integrating soil pools with biomass MRV; Spatial heterogeneity; deep rooting systems with scarce deep SOC measurements;

Dimension	Grasslands	Rangelands	Forests
	documenting management		legacy effects; disturbance uncertainty; limited field accessibility;
Typical MRV tier	Tier 2–3	Tier 3 only (Tier 1 unusable)	Tier 2 for national reporting ; Tier 3 recommended for projects
SOC permanence risk	Medium	High (droughts, degradation)	Low–medium: vulnerable to fire and other disturbances; land-use change
Strengths	Predictable, manageable, measurable	Large areas with restoration potential	Large carbon stocks; long-term sequestration potential; strong remote-sensing use; forest inventories in many countries; strong policy frameworks
Limitations	Sensitive to management change	High uncertainty; complex governance	Requires long-term commitment, slow SOC changes; expensive sampling; disturbance-driven changes; uncertainty in deep-soil carbon stocks

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1. Introduction

Over the last 8000 years, agriculture has had a significant impact on the atmospheric concentration of CO₂ and CH₄ (Salinger, 2007) and cultivated soils have lost around 116 Gt C (~510–550 Gt CO₂; Sanderman et al. 2017). There is potential to restore at least part of this lost carbon, but also room for more carbon lost depending on future developments of agriculture. Land-use change associated to replacement of forests or grasslands by croplands is a significant factor affecting soil organic carbon (SOC) stocks. Some management practices for crops, and long-time established permanent pasture may restore part of the lost carbon in soil, while the carbon lost in biomass cannot as easily be recovered without stopping agriculture and letting natural biomass regrow.

To foster carbon sequestration in agricultural soils and avoid more carbon losses, various frameworks for greenhouse gases emissions reductions and soil organic carbon change evaluation have been proposed, at diverse scales and for diverse actors. The NDC from the Paris agreement, at the scale of state actors targets the national scale. Voluntary or mandatory carbon markets or agricultural and environmental policies target businesses and economic actors. Such frameworks are typically associated to monitoring, reporting and validation (MRV) systems that allow to verify that the intended carbon sequestration or reduction of GHG emissions are actually achieved. See deliverable D4.1 and D4.2 for more in-depth analyses.

In-depth analysis of MRV systems for SOC change in croplands were the subject of deliverable D4.2. Here, we build on this work by adding recommendations for MRV systems for SOC change for other land uses, namely grasslands and rangelands and forests by reviewing existing literature and MRV frameworks. The differences of these ecosystems with croplands are described through an analysis of the specificity of these land uses, such as the importance of livestock management for grasslands and rangelands SOC MRV. All the facets of SOC change monitoring for grasslands and forests are reviewed and compared to croplands, including differences in temporal and spatial features, in input data, baseline determination, management diversity, models and earth system data, following the analysis set forth in deliverable D4.2, which looked in details at those features for croplands.

As exemplified by the historical SOC change, land use change has at least as much potential for SOC change than changes of practice for an unchanged land use. Review and recommendations on multi-ecosystem MRV frameworks are developed in the deliverable, focused on monitoring options for SOC changes associated to land use change to complete the recommendations for each land use previously obtained. Taking into account the possibility of land-use change leads to specific considerations for the design of MRV systems, by adding the possibility to protect from change land uses containing more SOC (Beillouin et al. 2021, 2023).

Land use change does not only lead to a change in SOC, but also in production. As demand change is usually considered out of scope of SOC and GHG emissions MRV, a local change in production, both in quantity and in term of type of product will have distant effects, with change in productions elsewhere to compensate for the local change. Besides distant production changes, other transfers and leakage

may have unintended consequences on SOC and GHG emissions in the scope of MRV frameworks. In particular carbon transfers through organic input, changes in GHG emissions, changes in input uses. The different transfers and leakages are described in the deliverable, with recommendations on MRV systems design, allowing to have a complete analysis with recommendations on the SOC MRV systems.

2. Methods for SOC MRV

2.1 MRV methods for grasslands and rangelands SOC

Globally, grasslands are among the largest ecosystems and cover around 3.5 billion-hectare (ha) area, representing 26% of the world land area and 70% of the world agricultural area. These grassland soils contain about 20% of the world's soil organic carbon (SOC) stocks (FAO, 2023). Grassland and rangelands are mainly managed for ruminant livestock production. Ruminant livestock systems range from low-input pastoral production systems in arid and semiarid environments to highly intensive production in more mesic environments, integrating livestock-crop-forage systems. In Europe (except for UK and Ireland) and South Asia it typically occupies less than 20% whereas global coverage for most continental regions is slightly less than 50% of total land area. In Central Asia, it can reach up to 70%. Carbon balance and SOC in pasture lands are therefore impacted by livestock management, both through grass management, consumption by livestock or harvest, or more directly through transfers of organic carbon through livestock excretion during grazing and by organic fertilisation.

Animal production remains one of the most debated sectors in actual environmental science, particularly due to its contribution to climate change. According to recent estimates, livestock farming accounts for approximately 12% of global anthropogenic greenhouse gas (GHG) emissions, representing nearly 40% of the total emissions from agri-food systems (FAO, 2023). Methane (CH₄) is the dominant contributor, responsible for more than half of livestock-related emissions, followed by carbon dioxide (CO₂, ~30%) and nitrous oxide (N₂O, ~15%). Since “livestock’s long shadow” (FAO, 2006), these figures have placed livestock systems at the centre of scientific and societal debates, prompting significant research into mitigation options such as improved feeding strategies, manure management, and pasture-based carbon sequestration.

Beyond GHG emissions, livestock farming is also associated with other contested issues, including deforestation, land-use competition between feed and food production, groundwater pollution, and concerns related to meat consumption, public health, and animal welfare, especially in intensive production systems (Herrero et al., 2016; Alary et al., 2011). The sector, however, contributes to nearly 40% of agricultural GDP worldwide and provides livelihoods for over 1.3 billion people, including an estimated 430 million smallholder farmers (FAO, 2016). Considering the Global South, livestock plays a structuring role in rural economies and food security. In mixed crop-livestock systems—predominant in tropical regions—herds supply manure critical for maintaining soil fertility, provide animal traction for cultivation, and serve as a form of financial insurance in contexts where access to markets and formal banking is limited. They contribute to ecological balance by limiting bush encroachment,

maintaining biodiversity, enhancing nutrient cycling and seed dispersal, and improving water infiltration in soils across vast, marginal territories (Herrero et al., 2016).

These ecosystem services provisions and multi-functional roles of grasslands (Richter et al. 2021, 2024) highlight the necessity of considering livestock not merely as a driver of SOC in pastures and an emitter sector but as a critical component of socio-ecological systems. Indeed, in terms of services, grasslands play a central role in provisioning forage for livestock (Peyraud & Delagarde, 2013), and thereby sustaining the production of key foods for human consumption such as milk and meat (O'Mara, 2012). While mitigation of emissions remains essential, integrative MRV frameworks for SOC stock changes must also account for the positive contributions of livestock to soil fertility, carbon storage, and ecosystem resilience, particularly in tropical grasslands and rangelands. Such a balanced perspective is necessary to inform policies that reconcile climate objectives with food security, biodiversity conservation, and rural livelihoods (Ryschawy et al., 2017; Dumont et al., 2016).

2.1.2 State of the art on grasslands MRV systems

Integrating Soil Organic Carbon into grasslands and rangeland MRV Frameworks

Historically, climate change mitigation strategies first targeted the forestry sector, given its importance as the largest above-ground carbon reservoir. Over time, soils have gained recognition as an equally critical carbon sink, particularly through the management of soil organic matter, of which carbon accounts for about 50% (i.e. 4p1000 initiative, COP21, 2015). Today, soil management is acknowledged as a central lever for regulating soil health and fertility, water regulation and carbon fluxes. Within agriculture, soil carbon management is considered to hold the largest mitigation potential, particularly in grazing-based livestock systems that depend on rangelands and forage resources (Gerber et al., 2013). According to Bossio et al. (2020), SOC represent 9% of the mitigation potential of forests, and 47% of that of agriculture and grasslands. The maintenance or increase in SOC stock is one of the few options identified by the IPCC (IPCC, 2019) that can contribute simultaneously to climate change mitigation, combating land degradation and biodiversity loss, while improving food security.

Figure 1 shows the projected GHG emissions from livestock farming worldwide in 2050 and the potential for reductions (FAO, 2023). Among these, soil and pasture carbon sequestration appears as a significant and strategic lever, offering mitigation potential comparable to other major interventions. Its role is particularly relevant in grassland- and rangeland-based livestock systems, where vast areas of land can act and were reported (e.g. early synthesis Conant 2001, Minasny et al 2017) as important carbon sinks ranging from -1.3 to $+1.4$ t C ha⁻¹ yr⁻¹ (Graux et al. 2020). Grasslands could contribute up to 17% of this objective, notably through optimized grazing management. Well-adapted grazing systems, combining adjusted grazing intensity with optimized management practices, have the potential at the global scale to increase soil organic carbon (SOC) stocks by 0.18 to 0.41 t C ha⁻¹ yr⁻¹ (Dondini et al., 2023). Sequestration in soils and perennial pastures not only offsets methane emissions but also enhances ecosystem resilience, soil fertility, and forage productivity, thereby delivering strong co-benefits for sustainable livestock systems.

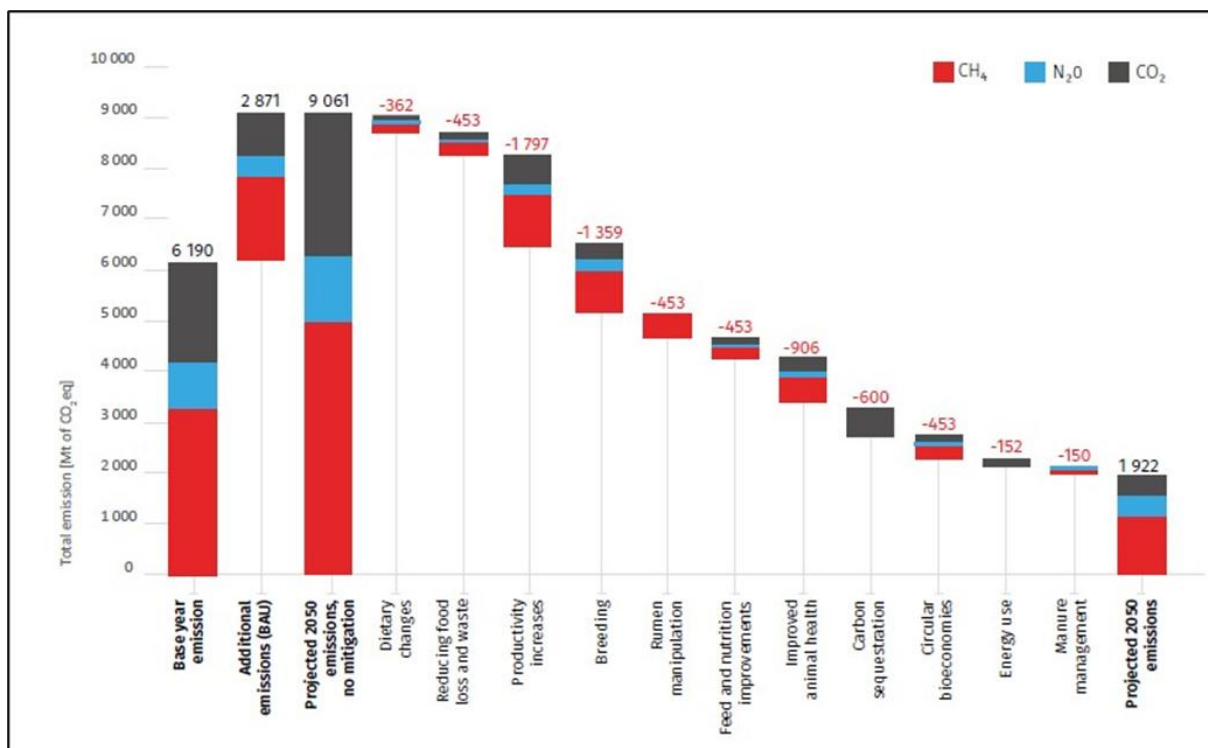


Figure 1: Greenhouse gas (GHG) emissions from livestock (base year emissions) and their projected trajectory towards 2050 under a business-as-usual (BAU) scenario. The left bar shows the current baseline emissions, estimated at 6,190 Mt CO₂-eq. The subsequent bars highlight the mitigation potential of different intervention strategies; Without additional mitigation measures, emissions are projected to increase to 9,061 Mt CO₂-eq by 2050, representing almost a 50% rise. (source FAO, 2023)

Livestock Systems and Soil Carbon

- **Tropical area**

Tropical pasture-based ruminant livestock systems, relying on either natural rangelands or sown pastures and managed through direct grazing or harvested forage, spanning from humid savannas to arid and semi-arid drylands, constitute critical reservoirs of Soil Organic Carbon (SOC) while sustaining the livelihoods of millions of pastoral and agropastoral households. Globally, they store approximately one-third of terrestrial carbon in soils (White et al., 2000; Conant et al., 2017). In tropical area, they are central to extensive livestock systems, particularly in Africa’s Sahelian belt, Brazil’s Cerrado, the Llanos of Colombia and Venezuela, East Africa’s savannas, and Northern Australia.

These ecosystems are characterized by:

- high inter-annual rainfall variability influencing biomass productivity and SOC dynamics

- low external inputs and extensive management (nomadism, transhumance, communal grazing)
- susceptibility to land degradation through overgrazing, fire use, and climate extremes.

Among agricultural systems, soil carbon management exhibits the highest mitigation potential, especially in livestock-based systems that depend on grazed and harvested forage resources (Gerber et al., 2013). For tropical grasslands and rangelands, this potential is especially relevant due to the vast areas involved.

Conventional metrics and methodologies for estimating soil organic carbon (SOC) are often poorly adapted to tropical rangelands, where strong spatial heterogeneity, complex grazing dynamics, and exposure to climatic extremes significantly influence SOC processes. The importance of carbon storage in the deeper soil layers is also a key factor. According to Stahl et al. (2016), carbon is primarily stored in the deep horizons of soils under pastures established after deforestation, with stocks measured down to one meter of depth.

In French Amazonia (French Guiana), Stahl et al. (2016, 2017) showed that in grasslands established after deforestation without the use of fire, soil organic carbon (SOC) stocks can recover to their pre-deforestation levels within approximately 24 years under management practices combining rotational grazing and legumes. Moreover, SOC accumulation continues beyond this point, particularly in deeper soil layers (below 1 m), (Fontaine et al., 2007, 2011).

Sequestration rates in such grassland systems can be substantial, reaching up to $1.27 \pm 0.37 \text{ t C ha}^{-1} \text{ yr}^{-1}$, primarily stored as SOC (Blanfort et al., 2022). Nevertheless, it is important to note that the carbon lost from forest biomass following deforestation represents a permanent deficit. Furthermore, systematic investigations of the impacts of land-use change on SOC remain scarce, particularly across regions such as North Africa, Central Africa, the Middle East, and Central Asia.

- **Temperate area**

In temperate systems, where management practices are highly heterogeneous, SOC sequestration rates vary widely, ranging from -0.40 to $+0.90 \text{ t C ha}^{-1} \text{ yr}^{-1}$ in Europe, with an average of $0.26 \pm 0.07 \text{ t C ha}^{-1} \text{ yr}^{-1}$. This range demonstrates that grasslands can, in certain situations, release substantial amounts of carbon or store only very little. Grasslands are therefore not perpetual carbon sinks, and it is essential to identify the conditions that favor SOC storage (Smith, 2014). The variability of SOC storage in grasslands is linked to grassland age, soil types, climatic conditions, botanical composition, and management practices, particularly the intensity of biomass removal (Conant et al., 2017; Sanderman et al., 2015; Abdalla et al., 2018).

Management types and intensities (grazing, mowing, fertilisation, species mixtures), vegetation covers, biomass production

Carbon storage capacity largely depends on pasture management, vegetation type, and environmental conditions (Jobbágy and Jackson, 2000; Cerri et al., 2004; McSherry and Ritchie, 2013).

- **Grazing and Mowing**

Grassland management practices related to modes of herbage use (grazing, mowing, or mixed) and to the intensity of exploitation relative to the grassland's production potential have a major impact on carbon storage. Practices influence carbon transfer to the soil either (i) by stimulating net primary production, thereby enhancing rooting and the supply of organic matter to the soil, or (ii) through the mode and intensity of herbage utilization, which affect the quantity and quality of plant litter being left on the field, i.e. senescent organic matter which is incorporated in to the soil, or by (iii) grazing practices that recycle part of the nutrients directly back to grasslands via animal excreta and thus contribute to primary production.

Mown grasslands generally sequester less carbon than grazed systems. Meta-analyses (Soussana et al., 2010; Conant et al., 2017; Bai et al., 2022) show that mowing reduces root biomass inputs compared to grazing, thereby limiting soil organic carbon (SOC) accumulation. The frequency and timing of mowing strongly influence SOC: frequent or early cuts can reduce aboveground biomass return and root growth, while late or less frequent mowing favors greater belowground C inputs (Gos et al., 2016). In European grasslands, SOC sequestration rates in mown systems are typically lower, often $<0.2 \text{ t C ha}^{-1} \text{ yr}^{-1}$, compared with grazed systems where values may reach $0.3\text{--}0.5 \text{ t C ha}^{-1} \text{ yr}^{-1}$ (Byrnes et al., 2018; Abdalla et al., 2018).

Regarding grazing, grazing intensity tends to reduce SOC sequestration potential under moist cool climates (-19.5%), whereas under dry warm and dry cool climates, higher grazing intensity may lead to SOC increases (Byrnes et al., 2018; Abdalla et al., 2018; Ritchie et al., 2020). Data compiled in the 4p1000 initiative support the findings of Byrnes et al. (2018), showing significantly lower SOC sequestration under continuous grazing ($0.19 \pm 0.08 \text{ t C ha}^{-1} \text{ yr}^{-1}$, $n=18$) compared with rotational grazing ($0.47 \pm 0.09 \text{ t C ha}^{-1} \text{ yr}^{-1}$, $n=30$). Overall, optimal grassland use appears to significantly enhance SOC and soil organic nitrogen sequestration (Ren et al., 2024). Across several studies, low to moderate biomass removal (30–70% of produced biomass) shows potential for SOC sequestration of 0.2 to $0.5 \text{ t C ha}^{-1} \text{ yr}^{-1}$, whereas high biomass removal ($>80\%$) is associated with SOC losses (Graux et al., 2020).

Meta-analyses comparing grazing strategies also indicate that rotational grazing (e.g. high-intensity, short-duration systems) tends to improve SOC storage and bulk density conditions relative to continuous grazing (Byrnes et al., 2018; Bai et al., 2022). However, the grass utilization rate (the ratio of grazed biomass to produced biomass) also appears to play a role, with higher SOC storage observed under rotational grazing when utilization rates fall within an intermediate range (0.5–0.8) compared with higher rates. At present, the limited number of available observations prevents drawing firm conclusions on all interacting factors (Byrnes et al., 2018). It is also important to acknowledge the wide diversity of both rotational and continuous grazing practices, which makes it problematic to compare them by reducing them to only two categories. Moreover, both grazing modes are often associated with specific pedoclimatic and vegetation conditions that interact with grazing effects on SOC storage. Finally, outside controlled experimental protocols, grassland and alpine pasture management often vary across seasons or years depending on pedoclimatic conditions and livestock needs, complicating the attribution of observed SOC changes to a single grazing management mode.

- **Fertilisation**

Fertilization plays a central role in intensive livestock production systems; however, due to environmental concerns, it is crucial to identify optimal management practices that balance productivity with carbon sequestration and biodiversity conservation. Inorganic fertilization generally increases aboveground plant biomass but is frequently associated with a trade-off in the form of reduced plant diversity. For instance, in the EU approximately 16% of mineral fertilizer use is applied to grasslands, with annual doses ranging from 0 to 200 kg N ha⁻¹. A recent global meta-analysis (Shi et al., 2024) reports that organic fertilization increases soil organic carbon (SOC) in grasslands by 19% relative to ambient conditions and 15% relative to inorganic fertilization, while at the same time maintaining plant diversity. The positive effect of organic fertilization on SOC was also found to increase with mean annual temperature.

Interactions between fertilization and grazing mode further influence SOC storage. Preliminary analyses (data under evaluation) suggest that fertilized grasslands under continuous grazing may store nearly twice as much carbon as those under rotational management. In contrast, for unfertilized grasslands, SOC storage levels appear similar between grazing modes.

- **Species mixtures**

The number and type of plant species composing permanent grasslands strongly influence carbon storage. Recent studies show that species-rich grasslands achieve higher C sequestration (Hungate et al., 2017; Lange et al., 2015; Bai et al., 2022). Carbon storage increases with plant species richness and the presence of legumes (Mueller et al., 2017; Rutledge et al., 2017). This effect is likely related to the diversity of root systems (ranging from shallow to deep and dense; Bondaruk et al., 2020), as well as to enhanced nitrogen availability provided by legumes, which in turn increases primary productivity. Overall, the introduction of new forage species—whether by increasing species number compared to monocultures (Yang et al., 2019; Elias et al., 2023), by incorporating functional groups such as legumes (Rutledge et al., 2017), or by adding deep-rooted species (Dignac et al., 2017)—has been shown to positively impact soil carbon storage (Bai et al., 2022; Conant et al., 2017).

- **Silvopastoral systems**

Silvopastoral grasslands generally enhance carbon sequestration compared to open pastures. The addition of trees increases above- and belowground biomass inputs and improves soil microclimate conditions for SOC stabilization (Jose, 2009; Nair et al., 2010). Recent meta-analyses indicate that silvopastoral systems can increase SOC stocks by 20–30% compared with treeless pastures, particularly in the topsoil (0–30 cm) (Torralba et al., 2016; Cardinael et al., 2018). In Mediterranean Europe, silvopastoral practices such as dehesas have been shown to sequester up to 0.4–0.6 t C ha⁻¹ yr⁻¹, depending on tree density and grazing intensity (Mosquera-Losada et al., 2017). Agroforestry systems additionally contribute to carbon storage through both above- and belowground tree biomass.

A case study from the Faidherbia albida agroforestry park in Niakhar (Senegal) provides new insights into root-mediated carbon dynamics (Siegwart et al., 2023). Although the role of Sahelian agro-silvopastoral systems in the carbon cycle and GHG fluxes remains insufficiently documented, research

indicates that root systems contribute significantly to SOC inputs, especially at depth where root litter decomposes more slowly. Long-term monitoring revealed that *Faidherbia* root biomass was unexpectedly greater at distances over 30 m from the trunk (30–100 cm soil layer), highlighting the tree’s extensive influence (Siegwart et al., 2023). Root litter inputs down to 150 cm accounted for 6.5% of total SOC inputs, underscoring the importance of deep-rooting species for enhancing soil carbon storage in semi-arid zones with inherently low SOC stocks. Increasing tree density or integrating deep-rooting crops thus emerges as a promising strategy for CO₂ mitigation.

In West African semi-arid and sub-humid regions, soil carbon sequestration is seen not only as a climate mitigation strategy but primarily as a means of sustaining soil fertility under resource-constrained conditions (Giller et al., 2021). Limited access to inputs, low mechanisation, poor soil fertility, and variable rainfall restrict the capacity for biomass production and, consequently, carbon sequestration. In this context, the recycling of crop residues is critical. However, trade-offs arise between their use as soil amendments and as livestock feed. While crop residues can be returned to fields to improve SOC, they also serve as a vital source of animal feed and manure production (Naudin et al., 2015).

SOC MRV systems for grassland and rangeland

The following table is a comparative overview of the main MRV approaches for SOC stock changes in pasture-based livestock systems from national GHG inventories guided by IPCC methodologies to voluntary carbon standards, research pilots, remote sensing and participatory territorial approaches. This synthesis underscores both the strengths and limitations of each approach, particularly in relation to their applicability in grasslands and rangelands, where livestock systems are central to livelihoods and carbon dynamics but where monitoring remains highly challenging. While some approaches (e.g., national inventories) provide global consistency and compliance with UNFCCC reporting requirements, they often lack the resolution to capture the heterogeneity of pastoral systems. On the contrary, innovative tools such as remote sensing, spectroscopy, and participatory MRV offer new opportunities for cost-effective, locally relevant monitoring, but require further calibration and institutionalisation.

Table 1: Pastures SOC monitoring approaches characterization

SOC monitoring approach	Examples of Use (Livestock/Pastures)	Strengths	Limitations (Uncertainty/Costs)	Relevance for NDCs	Key References
National GHG Inventories (IPCC Tiers 1–3)	LULUCF: SOC monitoring in grasslands/pastures; progression towards Tier 2 (national factors) and Tier 3 (models + measurements)	Recognised framework, temporal consistency, aligned with TCCCA*	Tier 1 too generic for tropical/pastoral systems; Tier 3 costly (deep sampling, bulk density, SOC fractions)	Official reporting basis; legitimises SOC integration in agriculture/livestock sectors	IPCC (2006; 2019 Refinement)

SOC monitoring approach	Examples of Use (Livestock/Pastures)	Strengths	Limitations (Uncertainty/Costs)	Relevance for NDCs	Key References
NDC Sub-Sector Mapping (CCAFS data & maps)	Identifies where countries include livestock and/or SOC; highlights regional gaps	Synthetic view, rapid identification of SOC/livestock priorities	Does not replace quantitative MRV; does not show measured outcomes	Helps target MRV needs and prioritise NDC reforms	CCAFS (2020–2024)
Livestock in NDC Analyses (transparency, indicators)	Status of livestock measures (manure, feed, animal health, silvopastoralism), non-GHG indicators	Highlights indicators, reference levels, quantitative targets to strengthen transparency	Few countries with GHG targets for livestock; limited affordable MRV	Clarifies how to detail the sub-sector for eligibility to climate finance	Rose <i>et al.</i> (2022)
SOC Framing in NDCs (ambition & obstacles)	Countries mention SOC or related practices (agroforestry, residues, restoration) without quantified targets	Shows SOC potential and co-benefits (adaptation, food security)	Major barriers: high costs, measurement challenges, production priority	Recommends SOC targets, capacity building, linking national policies and NDCs	Wiese (2019)
Voluntary Carbon Standards (pasture/SOC)	VCS/Verra (e.g., VM0026, VM0042), Gold Standard SOC: grassland management, rotation, silvopastoralism	Access to results-based finance; established sampling/model protocols	Costly measurements, permanence/reversal risk, verification logistics in extensive pastoralism	Useful complement to NDCs for scaling finance	Verra/Gold Standard
Research Pilots in Tropical Pastoral Systems	Sahel/Amazonia: multi-depth SOC sampling, livestock management integration, degradation detection	Captures heterogeneity (water points, gradients); shows possible carbon neutrality	Requires time series, costly fieldwork; limited upscaling	Proof-of-concept and basis for Tier 2/3 factors	
Remote Sensing & Spectroscopy (proximal/remote)	Sentinel/MODIS/UA V: biomass, cover, degradation; NIR/MIR for SOC	Low marginal cost at scale; frequent monitoring; data-model integration	SOC difficult to infer directly (depth, texture); local calibration required	Key tool for multi-scale MRV and uncertainty reduction	FAO-ITPS GSOCmap; EO-based Tier 3
Participatory & Territorial MRV (pastoralism)	Farmers/agricultural councils: grazing calendars, stocking rates, rangeland condition; FMIS/API integration	Lowers costs, enhances legitimacy, covers under-monitored zones	Data quality/standardisation issues; need for training and auditing	Strengthens transparency and links NDCs with territorial policies	Reported in NDC livestock commitments

* The UNFCCC has established five guiding principles—TCCCA—for the quality and credibility of national greenhouse gas (GHG) inventories and MRV systems:

- Transparency: Methods, data, and assumptions must be clearly explained and accessible.
- Comparability: Estimates should be reported consistently across countries and time.
- Consistency: The same methods should be applied over time and across sectors.
- Completeness: All relevant GHG sources and sinks should be included.
- Accuracy: Estimates should be as close as possible to true values, with reduced uncertainties.

Synthesis work was carried out to analyse MRV methods along with related details including version, link to the documentation and completion status (Black et al., 2023).

Table 2: MRV methods review from Black et al 2023

Table 2a. Analytical framework – documentation for the soil carbon MRV methods reviewed.

MRV method: documentation						
Title	Version year	Reference	Source URL	Status	Short-hand descriptor for MRV/code	
Measurement of Soil Carbon Sequestration in Agricultural Systems) Methodology Determination 2018	2018	[17]	www.cleanenergyregulator.gov.au/ERF/Pages/Choosing%20a%20project%20type/Opportunities%20for%20the%20land%20sector/Agricultural%20methods/The-measurement-of-soil-carbon-sequestration-in-agricultural-systems-method.aspx	Approved	AU1	
2021 Soil carbon method: proposed new method under the Emissions Reduction Fund	2021	[18]	https://consult.industry.gov.au/soil-carbon-method-proposed-new-method	Consultation (approved 12/2022)	AU2	
Protocol for Measurement, Monitoring, And Quantification of The Accrual of Below-Ground Carbon Over Time	2021	[19]	https://static1.squarespace.com/static/611691387b74c566a67f385d/t/6127d43cbc940c49c7b6cfdc/1630000191203/082621_Metrics_Protocol.pdf	Approved	BC	
Soil Enrichment Protocol V1.0 September 2020	2020	[20]	www.climateactionreserve.org/wp-content/uploads/2020/10/Soil-Enrichment-Protocol-V1.0.pdf	Approved	CAR	
Soil Organic Carbon Framework Methodology. Version 1.0. Published January 2020	2020	[21]	https://globalgoals.goldstandard.org/402-luf-agr-fm-soil-organic-carbon-framework-methodology/	Approved	GS	
A protocol for measurement, monitoring, reporting and verification of soil organic carbon in agricultural landscapes	2020	[22]	https://doi.org/10.4060/cb0509en	Approved	GSOC	
Carbon Agri Method, September 9, 2019	2019	[23]	www.ecologie.gouv.fr/sites/default/files/M%C3%A9thode%20C3%A9levages%20bovins%20et%20grandes%20cultures%20%28Carbon%20Agri%29.pdf	Approved	LBC1	
Field Crop Method, July 23, 2021, V1.1	2021	[24]	www.ecologie.gouv.fr/sites/default/files/M%C3%A9thode%20LBC%20Grandes%20cultures.pdf	Approved	LBC2	
Pilot Croplands Methodology Version 1.2 Last Updated: March 05, 2021	2021	[25]	https://storage.googleapis.com/nori-prod-cms-uploads/Nori_Croplands_Methodology_1_2_5435488110/Nori_Croplands_Methodology_1_2_5435488110.pdf	Pilot	NORI	
Adoption of Sustainable Agricultural Land Management. VM0017 Ver.1.0, Sectoral Scope 14	2011	[26]	https://verra.org/wp-content/uploads/2018/03/VM0017-SALM-Methodology-v1.0.pdf	Approved	VM17	
Soil Carbon Quantification Methodology. VM0021. Ver.1.0, Sectoral Scope 14	2012	[27]	https://verra.org/wp-content/uploads/2018/03/VM0021-Soil-Carbon-Quantification-Methodology-v1.0.pdf	Approved	VM21	
VM0042 Methodology for improved agricultural land management Ver.1.0 Sectoral Scope 14	2020	[28]	https://verra.org/wp-content/uploads/2020/10/VM0042_Methodology-for-Improved-Agricultural-Land-Management_v1.0.pdf	Approved	VM42	

- **The Verified Carbon Standard (VCS)**

The Verified Carbon Standard (VCS), managed by the non-profit organization Verra, is the world’s largest voluntary greenhouse gas (GHG) crediting program. It provides a framework for quantifying, monitoring, reporting, and verifying emission reductions and carbon sequestration activities across multiple sectors, including Agriculture, Forestry, and Other Land Uses (AFOLU). VCS is particularly important for pasture-based and silvopastoral systems, as it provides methodologies to account for soil organic carbon (SOC) sequestration and improved grassland management (rotational grazing, re-seeding degraded pastures, or integrating trees). This enables livestock projects to access results-based finance through carbon markets.

- **The MRV platforms**

The MRV Platform for Agriculture (AgMRV), an initiative by CGIAR’s CCAFS and the Global Research Alliance (GRA), is a comprehensive digital resource hub dedicated to supporting the design and implementation of Monitoring, Reporting, and Verification (MRV) systems in the agriculture sector, especially for livestock, rice, and agroforestry <https://www.agmrv.org/system/livestock/>

The AgLEDx Resource Platform, developed by CGIAR’s CCAFS program, is rooted in a comprehensive and multi-faceted methodology for low-emission agricultural development. It systematically integrates:

- UNFCCC & IPCC-Aligned GHG Inventory Guidance
 - The platform aligns with official frameworks such as the UNFCCC MRV principles and IPCC GHG Inventory Guidelines, offering methodological tools for estimating emissions from various agricultural sources—enteric fermentation, manure, soil carbon, land-use change, croplands, agroforestry, and more.
- Diverse Estimation Methods
 - AgLEDx provides curated descriptions of major estimation approaches, including:
 - Field measurements for direct SOC and GHG estimates, such as the SAMPLES protocol.
 - GHG emission calculators, ideal for quick approximations.
 - Statistical models to extrapolate results across contexts.
 - Process-based models like RothC, DNDC, DayCent, and others for detailed simulations.
- Scenario Modelling & MRV System Guidance
 - The platform guides users through:
 - Construction of baseline scenarios.
 - Development of measurement, reporting, and verification (MRV) systems tailored to national or sectoral contexts.
 - Integration of MRV with digital tools and policy planning.
- Support for Carbon Market Methodologies
 - AgLEDx includes foundational insights into carbon market standards—explaining how concepts like baselines, additionality, and leakage underpin MRV for emission reduction projects.

2.1.2 Methods and input for grassland SOC MRV

The information in this section complements the deliverable D4.2 on specific information different from cropland, the D4.2 should be consulted for generic information.

2.1.2.1 SOC Dynamics and implications for MRV

Croplands and pastures show contrasting patterns of Soil Organic Carbon (SOC) storage, with direct implications for SOC dynamics and monitoring. In croplands, SOC stocks are typically concentrated in the upper soil and are highly vulnerable to depletion due to tillage, residue removal, and frequent soil disturbance. Such disturbances accelerate organic matter mineralisation and limit the long-term stabilisation of carbon in deeper soil layers. By contrast, a number of studies (Fontaine et al. 2007, Hicks et al 2023, Button et al., 2022, Dubeux et al., 2024) have shown that permanent grasslands promote the accumulation of stable carbon pools in subsoil horizons, mainly below 30 cm, which are much less affected by cultivation. This stability is associated with continuous vegetation cover and related root system, providing an often dense root systems with continuous root turnover and rhizodeposition processes that enhance the incorporation of organic matter into mineral-associated fractions (e.g. Cotrufo & Lavelle, 2022, Cotrufo et al., 2019). These mechanisms explain why permanent pastures act as more durable carbon sinks compared to croplands, where repeated cultivation prevents significant carbon stabilisation at depth. This differentiation highlights the need for MRV frameworks to go beyond surface soil monitoring and include multi-depth sampling, especially in pasture systems, in order to accurately capture SOC sequestration potential and permanence.

From an MRV perspective, these differences imply that croplands require frequent surface soil measurements and careful tracking of management practices to detect SOC changes, while pastures demand multi-depth sampling and spatially explicit monitoring to capture heterogeneity and the influence of grazing patterns. Thus, while croplands present opportunities for SOC improvement through conservation agriculture, sustainably managed pastures represent more resilient and deeper carbon reservoirs, making their integration into MRV frameworks particularly critical.

Table 3: Differences between Croplands and Pastures for SOC sequestration dimensions and implications on SOC dynamics and monitoring

Dimension	Croplands	Pastures (Grasslands & Rangelands)	Direct Implications for SOC Dynamics & Monitoring (MRV)
SOC distribution	More concentrated in topsoil (0–30 cm) ; vulnerable to disturbance.	SOC extends into deeper horizons (up to 1 m) under permanent grasslands.	MRV in croplands requires frequent shallow sampling ; in pastures, multi-depth sampling is essential.
Land-use legacy	Conversion from forest/grassland → large SOC losses (≈15–30%). Recovery possible but slow.	Conversion from forest → initial losses; well-managed pastures can partially restore SOC.	MRV baselines must integrate land-use history (deforestation, cultivation cycles, pasture renewal).

Dimension	Croplands	Pastures (Grasslands & Rangelands)	Direct Implications for SOC Dynamics & Monitoring (MRV)
Carbon inputs	Depend on crop residues, rotations, fertilisers ; inputs seasonal and often removed.	Continuous root turnover, litter (residue) deposition, and manure return from grazing animals and fertilisation	MRV must track management practices in croplands vs. organic inputs and grazing patterns in pastures.
Stability of SOC	Gains are fragile, requiring continuous inputs and conservation practices.	SOC stocks more stable and resilient if pastures are not degraded.	Pastures offer longer-term sequestration potential ; croplands more prone to reversal.
Vegetation type	Mostly annual crops; low root biomass compared to grasses. Row and inter-rows	continuous cover, perennial grasses (C3/C4), legumes; dicots, higher root biomass and deeper rooting systems.	MRV must account for functional types (C3/C4, legumes) in SOC modeling and monitoring.
Degradation risks	Tillage, erosion, residue burning, mono-cropping.	Overgrazing, fire, erosion, land degradation.	MRV must include risk assessment indicators (erosion, grazing pressure).
Knowledge base	Long history of field trials and experiments in temperate croplands.	Less long-term data in tropical pastures, especially under pastoralism.	Strong need for capacity building, Tier 2/3 factors in tropical pastures.

2.1.2.2 Tropical and Temperate Systems differences related to SOC monitoring

Tropical pasture-based livestock systems differ from temperate systems in several ways, with direct implications for SOC dynamics and monitoring. Most of these differences stem from variations in climate, soil type, and texture. Land-use change strongly affects SOC sequestration in grassland. A global meta-analysis showed that land conversion, especially from forest to grassland and from grassland to cropland, has generated a substantial carbon loss (Beillouin et al. 2023, Poepflau et al. 2011). In particular in tropical regions, SOC is strongly influenced by the legacy of deforestation. The conversion of forests into pastures typically leads to immediate carbon losses, some of which may be gradually recovered through sustainable management practices such as rotational grazing or the use of legumes. Temperate permanent grasslands are generally long-established and only partially affected by such land-use history (approximately 40% of EU grasslands did not undergo LUC in the last 30yrs). In both cases forest biomass was lost.

Tropical rangelands such as those in the Sahel or the Brazilian Cerrado are exposed to pronounced climatic variability, including recurrent droughts, erratic rainfall, and frequent fires. These conditions increase the fragility and heterogeneity of SOC stocks compared with the more stable climatic regimes typical of temperate regions.

Vegetation composition differs markedly. Tropical systems are dominated by C4 grasses, which have distinct root structures, litter quality, and carbon turnover rates. Significant SOC gains in these systems

often depend on the integration of C3 legumes, which enhance nitrogen availability and improve soil fertility.

Livestock management practices in the tropics are shaped by extensive, communal, and mobile systems such as pastoralism and transhumance. This mobility generates strong spatial heterogeneity in SOC distribution, with hotspots around water points, pathways, and night enclosures, in contrast with the more sedentary, rotational, or intensive grazing systems of temperate regions.

Tropical grassland and rangelands systems may also have weak institutional capacity for sustained MRV operations (Batjes, 2019). The scarcity of historical baseline data common in tropical systems is also problematic, all the more when pastures were established recently. Together, these differences underline the unique challenges of monitoring, reporting, and verifying SOC dynamics in tropical livestock systems, while also pointing to their considerable, yet fragile, potential for carbon sequestration.

Although these aspects are particularly characteristic of tropical rangelands, many of them are also relevant, to a lesser extent, in temperate systems. In the tropics, these dynamics tend to be more pronounced due to higher climatic variability, distinct vegetation types, and extensive livestock management practices. By contrast, temperate systems, while less exposed to recurrent droughts, erratic rainfall, or fire, share similar underlying processes, albeit in a moderated form.

Table 4: Comparison of tropical and temperate livestock systems grasslands, rangelands and pastures characteristics and implications for SOC MRV

Dimension	Tropical Livestock Systems (Grasslands & Rangelands)	Temperate Livestock Systems (Grasslands & Pastures)	Implications for MRV of SOC
Land-use history	Strongly linked to deforestation and land conversion (e.g., Amazon, Central Africa). Initial SOC losses followed by partial recovery if pastures are maintained & well managed.	Generally long-established pastures, less tied to deforestation history, more to conversion into cropland. SOC stocks relatively stable for permanent productive area.	Need to capture land-use legacy (deforestation vs. pasture renewal) in SOC baselines for the last 10-20 yrs.
Vegetation types	Dominated by C4 grasses ; SOC increases when C3 legumes/shrubs are integrated (better N inputs).	Dominated by C3 grasses ; SOC dynamics more dependent on grazing intensity & fertilizer use.	MRV must account for C3–C4 interactions and species composition in tropics.
Climate & stressors	High variability: droughts, erratic rainfall, fire regimes. SOC stocks fragile & heterogeneous.	More stable climates, lower inter-annual variability, less fire pressure.	MRV frameworks need to integrate climate variability & fire impacts in tropical regions.
Grazing systems	Predominantly extensive, communal, mobile (pastoralism, transhumance) in some regions. Creates spatial heterogeneity in SOC (water points, corridors).	Predominantly sedentary, intensive or rotational grazing in private farms. SOC changes easier to attribute to management.	Tropical MRV must use spatially explicit, landscape-scale approaches (EO + participatory monitoring).

Dimension	Tropical Livestock Systems (Grasslands & Rangelands)	Temperate Livestock Systems (Grasslands & Pastures)	Implications for MRV of SOC
SOC vulnerability	Higher risk of rapid losses due to overgrazing, land-use change, temperature increases.	More stable SOC stocks; vulnerability mainly from tillage, land conversion, or over-grazing/fertilization.	SOC permanence is a major concern in tropical MRV; requires risk assessment and uncertainty tracking .
Knowledge gaps	Few long-term studies; limited systematic SOC assessments in Africa, Amazon, Asia.	More extensive data, long-term experiments available (Europe, North America).	Tropical MRV needs capacity building, long-term monitoring, and region-specific factors (Tier 2/3) .

2.1.2.3 Spatial and temporal boundaries

Spatial boundaries

The definition of spatial boundaries is particularly challenging in livestock-based grassland and rangeland systems, given their heterogeneity and the diversity of management practices. Livestock-based grassland and rangeland systems are characterized by high spatial heterogeneity, due to the mobility of herds, uneven manure deposition, and localized grazing hotspots (corridors, bomas, watering points).

- **Grasslands (cultivated or improved pastures):**

Grasslands are often established as sown or managed pastures, with relatively clear boundaries at the farm or plot scale. Many areas are distinguished between permanent grasslands (>5 years), which often host higher biodiversity and more stable SOC stocks, and temporary or sown grasslands with defined species mixtures, which are younger and generally more intensively managed. They may be fenced or otherwise delineated, facilitating stratification and sampling design. In such systems, SOC dynamics are largely influenced by management intensity (mowing, rotational vs. continuous grazing, fertilisation, reseeding), and spatial variation is more easily captured through field-level monitoring and farm-scale records. SOC monitoring in grasslands can therefore rely on a combination of plot-based soil sampling (including stratification and composite samples) and remote sensing indicators (e.g., NDVI, biomass indices) to account for variations in productivity and vegetation cover.

- **Rangelands (extensive and communal systems):**

Rangelands, in contrast, are typically extensive, open-access or communal lands that support transhumant or nomadic grazing. They often lack fixed boundaries and are characterised by large spatial extents, patchy degradation, and heterogeneous use patterns. Grazing pressure is uneven, with hotspots around water points, corridors, and bomas, while remote areas may be lightly grazed. This creates a mosaic of SOC dynamics that cannot be adequately captured by uniform sampling. The FAO SOC MRV guidelines (2019) recommend stratified sampling to distinguish heavily used areas from less disturbed zones, and to integrate land use history (deforestation, fire, abandonment) into the spatial

baseline. In tropical regions, rangelands also present marked variation in soil type and vegetation composition (C3 vs. C4 grasses, shrub cover), which must be accounted for in MRV frameworks.

In tropical rangelands—such as the Sahelian belt, East African savannas, or the Cerrado—spatial boundaries are diffuse and highly heterogeneous. Grazing is often mobile and communal, with intense pressure near watering points, transhumance corridors, and livestock camps (bomas), contrasted with undergrazed or remote areas. This mosaic requires landscape-scale MRV approaches that integrate stratified sampling, remote sensing, and participatory monitoring with herders (SOC MRV Sourcebook, 2021).

Temporal boundaries

On the temporal scale, SOC dynamics pastures differ from both forests and croplands. While forest SOC changes accumulate over decades to centuries, and cropland SOC responds within a few years to management shifts, grasslands and rangelands occupy an intermediate position. SOC variations can be detected over 5–10 year intervals, but their permanence is fragile due to recurrent climate events (droughts, fire events, hurricanes), and land-use changes.

- **Grasslands**

SOC changes in managed grasslands are generally detectable within monitoring cycles of 5–10 years, owing to more intensive management interventions such as fertilisation, reseeding, or rotational grazing. These practices can accelerate SOC sequestration, particularly in the topsoil, and monitoring frameworks can therefore adopt relatively frequent measurement or reporting intervals. Nonetheless, permanence remains a concern, as shifts in management (e.g., conversion back to cropping, overstocking) may quickly reverse SOC gains. FAO (2019) stresses the need for consistency in management documentation to ensure that observed SOC changes are attributable to actual practices. In tropical contexts, permanence is fragile: overgrazing, soil disturbance, or conversion back to crops can rapidly reverse gains. Regular cycles of measurement, coupled with documentation of management practices, are essential (FAO, 2020a).

- **Rangelands**

Temporal dynamics are slower than in permanent and cultivated sown grasslands: meaningful SOC changes often require periods of 10–20 years or more to be detected, due to extensive management, lower productivity, and the predominance of natural vegetation. Changes are often more gradual, and high interannual variability in rainfall, recurrent droughts fire, and grazing pressure can mask long-term trends.

The FAO CSOC MRV Protocol (2020) recommends adopting long-term monitoring horizons, explicitly accounting for disturbance and reversal risks, and using conservative estimates to address uncertainty. Unlike grasslands, which may be resampled at farm scale, rangelands demand landscape-level baselines with permanent observation plots and periodic “true-up” campaigns to confirm modeled SOC trajectories.

2.1.2.4 Setting the baseline

Establishing a robust baseline is a critical step for SOC MRV in grassland and rangeland systems. Unlike croplands, where management interventions and SOC dynamics can be linked to recent and well-documented shifts in practices, grasslands and rangelands often operate under longer temporal horizons and slower SOC dynamics. These differences highlight the need for tailored MRV protocols: cropland monitoring can rely more on farm-scale records and standardized methods, whereas rangeland MRV must integrate land-use history, mobility of livestock in tropical systems, and landscape-level variability to ensure credibility and alignment with NDCs.

Long-term perspective and persistence

In these systems, baselines must integrate both historical land-use trajectories and ecological persistence, since SOC changes unfold over decades rather than years (FAO, 2019). SOC dynamics in pastures unfold over decades rather than years. In tropical systems, where pastures often originate from deforestation or conversion of natural ecosystems, initial SOC losses are followed by partial recovery under managed grazing. Conversion of forests to pastures typically leads to initial SOC losses, followed by partial recovery under well-managed grazing systems (rotational grazing, reseeded, legume integration). However, permanence remains fragile: droughts, fire events, and overgrazing can quickly reverse gains. This highlights the need for baselines that integrate both long-term potential trajectories and short-term risks of reversal (FAO, 2019; FAO CSOC MRV Protocol, 2020).

Spatial and social context

Grassland farming system, like croplands, can have their baselines set at the field scale. Rangelands, however, require landscape-level reference scenarios. Baselines in rangelands should be spatially explicit, reflecting the high variability induced by mobility, communal grazing, and fire regimes (World Bank, 2021). Heterogeneous grazing pressure near corridors, water points, and temporary camps produces patchy SOC distributions. The FAO SOC MRV Protocol (2020) recommends conservative, stratified baselines that account for this variability and uncertainty. Moreover, because local herders play a central role in defining grazing patterns, participatory baseline establishment is critical to capture management practices not visible from remote sensing.

Land-use legacy and management history

Baselines must reflect both the legacy of conversion and the trajectory of long-term management. FAO (2019) and the World Bank SOC MRV Sourcebook (2021) stress the need to adopt baselines that extend beyond short monitoring cycles, recognising the persistence and reversibility of SOC stocks. Pasture baselines in tropical zones must integrate the historical trajectory of land use. For instance, forest-to-pasture conversion results in permanent losses of aboveground biomass carbon, but SOC may stabilise or even increase under well-managed systems (e.g., rotational grazing, legume introduction). Conversely, overgrazing, fire regimes, and land degradation drive rapid SOC depletion. Therefore, baseline establishment requires combining remote sensing archives (land-use change detection) with ground-level surveys of current management practices (grazing intensity, reseeded, fertilisation).

Measurement and modelling approaches for baselines

Baseline SOC stocks can, as a first guess, be approximated using IPCC Tier 1 defaults, but moving towards Tier 2/3 approaches is necessary due to high variability of management practices and intensities. Process-based models such as RothC, Century, or DayCent, calibrated with local data, provide more robust estimates. The Soil Enrichment Protocol (2020) and Lavallee et al. (2024) modelling guidance highlight the importance of calibration, validation, and conservative uncertainty deductions to avoid overestimation of sequestration potential.

- Measured baselines: Direct soil sampling provides high accuracy but is costly and logistically demanding.
- Modeled baselines: Process-based models (e.g., RothC, Century, DayCent) calibrated with local data allow upscaling and scenario testing.
- Dynamic baselines: Adjust over time to incorporate climatic variability, land-use change, or management evolution.
- Static baselines: Fixed reference levels defined at a given point, simpler but less representative of SOC dynamics.
- Plot-specific vs. standardised: Plot-specific baselines reflect local realities, whereas standardised approaches (e.g., regional statistics, default values) enable consistency across regions.

Uncertainty and permanence

SOC baselines in tropical and temperate grasslands and rangelands must explicitly address the fragility of SOC stocks. As highlighted by FAO (2019), sequestration gains may be quickly reversed by climate hazards (droughts, fires), overgrazing, or land conversion. Therefore, baselines must integrate risk buffers and uncertainty ranges in line with MRV principles of transparency and be conservative. This is particularly important for their inclusion in NDCs and carbon market instruments, where permanence is a prerequisite for crediting.

Table 5: Key differences in SOC baselines between croplands and grasslands/rangelands

Dimension	Croplands	Grasslands & Rangelands
Temporal dynamics	Short-term rapid changes (<10 years); SOC may respond rapidly to tillage, residue management, and rotations, depending on type of soil.	Long-term changes (temperate 5-10 yrs; tropical 10–20+ years); SOC accumulates gradually but is vulnerable to droughts, fire, and overgrazing.
Permanence	Fragile due to frequent disturbance (tillage, residue export, crop conversion).	Fragile due to climatic extremes, mobility, and land-use conversion; requires explicit permanence safeguards.

Dimension	Croplands	Grasslands & Rangelands
Land-use legacy	Often linked to recent management changes; farm records and statistics widely available.	Strongly tied to deforestation history, conversion to cropland and long-standing grazing regimes; historical reconstruction often needed.
SOC depth	More concentrated in topsoil (0–30 cm).	Significant storage in deep horizons (20–100 cm), especially under C4 grasses and permanent pastures.
Spatial boundaries	Well-defined at field or farm scale; private ownership simplifies monitoring.	Diffuse, communal or open-access lands; high spatial heterogeneity, hotspots (corridors, bomas, watering points).
Data availability	Supported by long-term experiments (e.g., Rothamsted, LUCAS); high-resolution data accessible.	Limited long-term SOC datasets in tropics; baselines often rely on Tier 1 defaults; higher uncertainty.
Baseline definition	Farm or plot-level; relatively homogeneous systems.	Landscape-level; requires stratification, remote sensing, and participatory MRV approaches.

2.1.2.4 Input data

In croplands, input data requirements focus heavily on tillage practices, residue management, fertilization, and soil sampling. Grasslands demand deeper soil measurements, spatially explicit grazing, mowing and fertilisation data, and disturbance records (fire, drought). This highlights the necessity of tailoring MRV frameworks to the ecological and management realities of grassland (grazing) systems rather than extrapolating from cropland methodologies. These ecosystems differ from croplands in their management practices, ecological dynamics, and spatial heterogeneity. Four key categories of input data are required:

Soil Carbon Measurements and soil Properties

SOC measurements remain the backbone of MRV frameworks. In tropical pastures, SOC is often stored at greater depths (20–100 cm) compared to croplands where SOC is concentrated in the top 30 cm. Thus, multi-depth sampling is essential, preferably down to 1 m or at least 0-60cm, using harmonized methods such as equivalent soil mass approaches to avoid bias from bulk density differences (FAO, 2019; GSOC-MRV Protocol, 2020, Verra). High-frequency sampling is particularly needed in degraded rangelands where SOC losses may occur rapidly following overgrazing or fire. Soil sampling should comprise stratification of the area in order to account for topography, degradation, vegetation cover and boundaries (hedges, roads, ...)

Beyond SOC concentration, classic key soil parameters must be collected to support accurate modeling and upscaling (such as soil type, stoniness, bulk density, clay content and pH).

Biomass Data

Biomass sampling in grasslands plays a critical role in understanding the dynamics of soil organic carbon (SOC) stocks, as both aboveground and belowground biomass determine the magnitude and quality of carbon inputs to the soil. Species composition, such as the proportion of C3 versus C4 grasses

or the presence of legumes and shrubs, strongly influences carbon turnover rates and nutrient cycling, with legumes contributing additional nitrogen that enhances SOC stabilization.

Monitoring approaches increasingly combine traditional biomass harvests with the assessment of plant functional traits (e.g., perennial vs. annual species, rooting depth, photosynthetic pathways), which provide valuable proxies for SOC dynamics.

Remote sensing indicators, particularly vegetation indices such as NDVI (Normalized Difference Vegetation Index) or EVI (Enhanced Vegetation Index), offer scalable tools to monitor grassland productivity, canopy cover, and degradation trends.

Integrating these ground-based and EO-derived measurements within Monitoring, Reporting and Verification (MRV) systems is essential to link biomass variability with long-term SOC sequestration potential under different grassland management regimes.

Climate Data

SOC dynamics in tropical grasslands are strongly climate-sensitive, process-based models and accurate MRV. FAO (2020) and Lavallee et al. (2024) requires high-resolution datasets of:

- Rainfall quantity and distribution, critical for pasture productivity and SOC inputs.
- Drought and fire occurrence indices, which represent major disturbances in savannas and semi-arid rangelands.
- Management Practices in Grazing Livestock Systems

Management data are indispensable for linking livestock activity to SOC outcomes. Key parameters include:

- Livestock management: Stocking rates (heads /ha) and grazing intensity (rotational vs. continuous systems), herd mobility, transhumance patterns, and manure deposition patterns (corridors, water points, bomas).
- Pasture management: fertilisation, irrigation, fire use/suppression, and restoration practices (reseeding). Organic amendments: manure, compost, and their recycling across crop-livestock systems (FAO & ITPS, 2018).

The Soil Enrichment Protocol (2020) and GSOC-MRV guidelines recommend harmonized recording of management data, supported by participatory monitoring with herders and the use of digital farm management platforms

Disturbance and Land-Use Data

Fire frequency, overgrazing, erosion, and conversion events (e.g., forest-to-pasture, pasture-to-cropland) must be documented, as they significantly affect SOC permanence.

Historical land-use datasets and remote sensing archives are critical for establishing baselines and reconstructing SOC trajectories.

Socio-economic and Institutional Data

In communal rangelands, information on tenure, governance, and collective management rules can explain spatial heterogeneity in SOC outcomes. Participatory data collection involving herders and pastoral associations enhances accuracy and legitimacy of MRV systems (FAO, 2019).

Table 6: Comparative Input Data Requirements for SOC MRV in Croplands vs. Grasslands/Rangelands

Dimension	Croplands	Grasslands & Rangelands (Tropics)
Activity data	Tillage type, crop rotations, residue retention/removal, fertiliser & manure use, cover crops.	Stocking rates, grazing intensity & mobility, transhumance, manure deposition hotspots, fire, reseeding, fertilisation, irrigation.
Soil data	SOC concentration and bulk density mainly in 0–30 cm; occasional subsoil sampling (important for changes in SOC).	SOC sampling beyond 30 cm (up to 1 m) due to deep-rooted C4 grasses; stoniness, texture, mineralogy also relevant.
Vegetation data	Crop type, yield, residue quality/quantity, crop calendars; EO integrated with crop models.	Aboveground biomass, C3/C4 species balance, legumes, canopy cover; EO indices (NDVI, EVI) to monitor forage productivity and degradation.
Climate data	Precipitation and temperature affecting productivity and decomposition; lower variability.	Rainfall and temperature variability, drought, fire regimes, and temperature extremes strongly affect SOC dynamics.
Disturbance/land use	Conversion to/from cropland, tillage intensity, organic amendments.	Deforestation-to-pasture and cropland to grassland conversion, overgrazing, erosion, bush encroachment, fire scars, degradation mosaics.
Data availability	Well-documented in some contexts, through farm records, national statistics, and long-term field experiments.	Limited systematic monitoring; participatory herder input, EO data, and stratified surveys essential.

2.1.2.5 Decision support tools

Decision-support tools (DSTs) are essential for operationalizing MRV frameworks in tropical grasslands and rangelands, where monitoring SOC dynamics is constrained by high spatial heterogeneity, scarce long-term data, and limited institutional capacities in global south context. They enable stakeholders to integrate field measurements, models, and remote sensing into consistent frameworks for reporting under NDCs and carbon market protocols.

- IPCC Tier 1–2 calculators (e.g., FAO’s EX-ACT, Cool Farm Tool) provide entry-level estimates of SOC change by linking livestock management practices to emission factors and simple carbon

balance approaches. These are valuable in data-poor tropical contexts but are often too coarse to capture variability in rangeland systems (FAO, 2019).

- The GSOC-MRV Protocol (FAO, 2020a) emphasizes progressive improvement towards Tier 3 models (e.g., RothC, CENTURY, DayCent), which allow dynamic simulation of SOC under rotational grazing, fire management, and drought scenarios.
- Remote Sensing and Digital Tools combining EO with Tier3 models

GSOCmap (FAO) and Earth Observation platforms support stratification of landscapes and identification of degradation hotspots, particularly in semi-arid rangelands where direct sampling is sparse (World Bank, 2021).

Proximal sensing and spectroscopy tools are increasingly used to complement laboratory SOC analyses, enabling faster, cost-effective monitoring at scale. Lavalée et al. (2024) stresses that integrating satellite data with process-based models enhances spatial accuracy but requires calibration with local soil and management data.

Livestock-Oriented Decision Tools

The Global Livestock Environmental Assessment Model (GLEAM) is a FAO-developed GIS (geographic information system) framework (<https://www.fao.org/gleam/resources/en/>), that simulates the biophysical processes and activities along livestock supply chains under a life cycle assessment approach. The aim of GLEAM is to quantify production and use of natural resources in the livestock sector and to identify environmental impacts of livestock in order to contribute to the assessment of adaptation and mitigation scenarios to move towards a more sustainable livestock sector.

GLEAM-i, The Global Livestock Environmental Assessment Model interactive is a free and accessible version of GLEAM that incorporates livestock activity data and functions as a Tier 2 instrument for livestock-related GHG emissions evaluation based on a Life Cycle Assessment Approach. It is specifically designed to support governments, project planners, producers, industries, and civil society organizations in estimating greenhouse gas (GHG) emissions across livestock production systems.

GLEAM-i does integrate Soil Organic Carbon (SOC) via its underlying modelling framework as extended by the FAO and the Livestock Environmental Assessment and Performance (LEAP) Partnership. The soil module incorporates the RothC model, which calculates SOC stocks based on inputs such as manure-derived nitrogen, crop residues, soil properties, and climate. It simulates carbon sequestration and losses over time, aligning with Tier 2 MRV needs. Participatory MRV platforms (e.g., community-based mobile apps, pastoral information systems) allow herders to record grazing intensity, fire events, and manure deposition patterns, which are critical for SOC models in extensive rangelands.

The AgriClimateChange Tools (ACCT) farm tools have been adapted to tropical contexts including French Guiana and the Brazilian Amazon (AgriClimateChange Tools (ACCT) (Da Cruz et al., 2025, Dallaporta et al., 2016). Originally developed in Europe, ACCT has been adapted to French Guiana and the Brazilian Amazon to account for deforestation, soil C storage, and livestock GHG emissions. The tool combines energy balances, GHG inventories, and SOC stock variations, integrating Tier 2 IPCC methodologies. The tool has been localized through participatory research with livestock farmers, enabling context-specific coefficients for fuel use, fertilizer, and manure management. This



participatory element enhances data reliability and supports farmer engagement in carbon monitoring, consistent with the 4p1000 Initiative’s recommendations for overseas tropical regions (Demenois et al, 2023).

Carbon Market and Verification-Oriented Tools

Verra’s VM0042 (Grasslands and Shrublands Methodology) and related protocols also incorporate remote-sensing-based monitoring and project aggregation, suited for tropical communal rangelands. Current carbon market mechanisms and protocols have been extensively reviewed, for instance in the overview of domestic carbon standards in Europe (Cevallos, Grimault & Bellassen, 2021), the proposal of a modular, multi-ecosystem MRV framework for SOC stock change assessment (Batjes et al., 2024), and the synthesis of agricultural soil carbon credit protocols by Oldfield et al. (2021 EDF report). Together, these works highlight both the diversity of existing standards and the need for harmonized, robust, and scalable approaches to Monitoring, Reporting and Verification (MRV) in order to ensure credibility, comparability, and long-term effectiveness of carbon markets.

Comparative Perspective with Croplands

Compared to croplands, where DSTs focus primarily on tillage, residue management, and fertilization practices, grassland and rangeland DSTs must integrate spatially explicit grazing dynamics, fire regimes, and livestock mobility patterns. This requires coupling biophysical models with participatory, landscape-scale monitoring to ensure both accuracy and legitimacy of SOC MRV in tropical systems. All in all, cropland DST are more used outside of the research community, but DST for grasslands and rangelands are taking the same path and closing the gap in term of usability.

Table 7: Comparative Decision-Support Tools for SOC MRV in Croplands vs. Grasslands/Rangelands

Category	Croplands	Grasslands & Rangelands
Empirical calculators (Tier 1–2)	EX-ACT, Cool Farm Tool, IPCC emission factor calculators based on tillage, residue, fertilisation.	EX-ACT (pasture modules), GLEAM-i (livestock emissions + RothC linkage); Tier 1 defaults for grazing pressure and fire.
Process-based models (Tier 3)	RothC, CENTURY, DayCent widely calibrated on cropping experiments (e.g., LUCAS, Rothamsted).	RothC, CENTURY, DayCent , AMG, CometFarm, Agrecalc, applicable but require calibration for grazing intensity, manure deposition, fire, and drought dynamics.
Remote sensing & EO tools	Satellite-derived crop productivity maps, residue cover detection, and yield estimates.	GSOCmap (FAO), RCTM (Xia et al. 2025), NDVI/EVI indices for biomass & degradation, fire scar detection; crucial for vast communal rangelands.
Proximal sensing & spectroscopy	Used mainly to monitor SOC in ploughed topsoil (0–30 cm).	Applied for multi-depth SOC monitoring in heterogeneous pastures; complements field sampling in deep-rooted systems.
Participatory & digital tools	Farm record systems, extension service data, national agricultural statistics.	Community-based MRV apps, pastoral information systems for grazing, fire, manure tracking; essential in mobile herding systems.

Category	Croplands	Grasslands & Rangelands
Carbon market & verification tools	Soil Enrichment Protocol (CAR, 2020); Verra VM0042 (cropland restoration).	Soil Enrichment Protocol; Verra VM0042 adapted to grasslands/shrublands; project aggregation crucial in communal rangelands.
Key MRV implications	Standardised, farm-scale MRV possible; relatively homogeneous datasets.	Requires spatially explicit, landscape-scale MRV; heterogeneity, mobility, and climate variability demand more complex DST integration.

2.1.2.6 Earth observation data, radiative transfer and assimilation

Remote sensing provides frequent, large-scale observations of vegetation and soil conditions, relevant for grasslands and rangelands monitoring. Still, the direct interpretation of satellite and drone imagery is often limited by atmospheric effects, sensor noise, complex interactions and indirect biophysical relationships between electromagnetic signals and vegetation (Rees, 2013). The most relevant example of an indirect biophysical relationship is the use of vegetation indices (e.g., NDVI) to infer vegetation properties but do not provide direct estimates of variables like LAI, chlorophyll content, or crop phenology (Carlson et al. 1997, Camps-Valls et al. 2021). To overcome these limitations, radiative transfer models (RTMs) are used to simulate how electromagnetic radiation interacts with soil, vegetation, and the atmosphere via scattered, absorbed, and transmitted through different media, enabling retrieval of biophysical parameters (Jacquemoud & Ustin, 2019; Weiss et al. 2020). The result is relevant parameters related to vegetation growth, land management and soil properties relevant for SOC monitoring or verification. Concerning SOC, remote sensing techniques primarily estimate SOC at the soil surface only, as deeper soil carbon content is not directly observable from optical or radar sensors (Gomez et al. 2008). As a result, vegetation monitoring becomes crucial for assessing overall carbon sequestration since plant growth, biomass accumulation, and residue management influence soil carbon inputs. The integration of RTM-based estimates of biogeophysical parameters into plant, ecosystem or soil models improves carbon budget assessments and supports carbon farming initiatives. The application of RTMs in agricultural remote sensing has advanced significantly in recent years, enabling the retrieval of crucial agricultural parameters (Weiss et al. 2020). The ability to estimate biogeophysical parameters (e.g., LAI, biomass, soil moisture, SOC content) and agricultural practices (e.g., cutting, tillage) using RTMs has greatly improved grassland monitoring (Franke et al. 2012, De Vroey et al. 2021, Holtgrave et al. 2023, Watzig et al. 2023).

RTM models are used to simulate spectral responses (reflectances) that are then inverted to estimate biogeophysical parameters. RTMs apply to both satellite-based and drone-based remote sensing data, improving their interpretability and enabling accurate agricultural monitoring. Several RTMs have been developed to represent vegetation and soil characteristics. 1D canopy models assume a horizontally homogeneous canopy (e.g., PROSAIL, PROSPECT-D) (Jacquemoud et al. 2009, Féret et al. 2017). They are the most widely used and the most adapted for practical applications. On the other hand, 3D canopy models, while representing heterogeneous vegetation structures and explicit directional effects (e.g., DART; Gastellu-Etchegorry et al. 2017) have greatly advanced in recent years but they remain less adapted for large-scale applications, mainly because of the need for detailed vegetation (e.g. 3D architecture) and soil description. Coupled canopy-atmosphere RTMs that integrate vegetation, soil, and atmospheric interactions (e.g., Modtran and PROSAIL) are less often used for satellite remote sensing data that are often provided at the top of the canopy reflectances or backscatter. They are more commonly used for drone data to take into account atmospheric effects. Currently, in the vast majority of the applications make use of empirical and machine learning based approaches, more so when SAR and microwave data is used.

The main aim of the use of RTMs in agricultural applications is to retrieve biophysical parameters from remote sensing data. Key biophysical parameters include:

- **Leaf Area Index (LAI) and Green Leaf Area Index (GLAI)** are crucial indicators of vegetation development. They are retrieved using canopy RTMs such as PROSAIL by matching simulated and observed spectral reflectance (Jacquemoud *et al.* 2009). Statistical empirical models are also used to retrieve LAI based on SAR data.
- **Biomass and vegetation water contents** are mainly retrieved from inverting active or passive microwave RTMs, because of the penetration depth of microwave signals. Water Cloud Model (WCM) is the most widely used empirical RTM that relates radar backscatter (e.g., Sentinel-1 SAR) to vegetation structure, water content and soil conditions. Other models like Tau-Omega Models account for vegetation attenuation and scattering to estimate Volumetric Water Content (VWC) and Vegetation Optical Depth (VOD) from passive microwave data using L-band or from C-band wavelength (Kerr *et al.* 2012). The VOD from passive microwave is not adapted for crop applications as the microwave sensors (e.g. SMOS, SMAP) have low spatial resolutions.
- **Chlorophyll and Nitrogen Content** Leaf-level models (e.g., PROSPECT, PROSPECT-D) simulate leaf spectral properties to retrieve chlorophyll and nitrogen contents, which are essential for assessing plant stress and nutrition (Féret *et al.* 2017).
- **Surface Soil Moisture and Soil Surface Roughness:** surface soil moisture and surface roughness (related to soil work) are key factors affecting carbon decomposition processes. Radar backscatter models like Integral Equation Model (IEM) (Fung *et al.* 1992; Oh 2004; Dubois *et al.* 1995) and the Water Cloud Model can track these variables as they are sensitive to soil moisture, surface roughness, and vegetation structure. Surface soil moisture is best retrieved from passive microwave at long wave length (Al Bitar *et al.* 2017), but in this case the spatial resolution is very low. Zribi *et al.* (2019) applied the WCM in semi-arid regions on cropland to retrieve soil moisture from L-Band SAR data. Fusion algorithms using SAR and microwave data are used to retrieve high resolution soil moisture taking advantage of the two technologies (Tomer *et al.* 2016). El hajj *et al.* (2017) suggested the use of optical and radar data for surface soil moisture. However, root zone (>5cm depth) soil moisture is a more adequate information for soil carbon models. Root zone soil moisture is not directly observed by existing satellite sensors. It can be retrieved either by statistical models (Souissi *et al.* 2022) or via assimilation into land surface models (Pique *et al.* 2020).
- **Surface soil organic carbon (SOC)** can be estimated using hyperspectral and multispectral reflectance data (Gomez *et al.* 2008, Nocita *et al.* 2013) as SOC influences soil reflectance in visible (400–700 nm) and shortwave infrared (1000–2500 nm) bands due to organic matter absorption. As in grassland ecosystems the soil is covered most of the time by vegetation superficial SOC content can rarely be observed by remote sensing. Concrete applications of retrieval of surface SOC from remote sensing are based on empirical statistical methods, Random Forest (RF), multi linear regressions (MLR), Support Vector Machine (SVM), Artificial Neural Networks (ANN) (Vaudour *et al.* 2022). Since these estimates apply only to the surface layer, while deeper SOC must be inferred from models integrating land-use history and carbon inputs from vegetation (e.g. Peng *et al.* 2024).

As mentioned in previous sections, EO based indices or retrieved biophysical parameters from RTMs inversion can also be used to monitor agricultural practices. Time series analysis of optical remote sensing (e.g. Sentinel-2) are also widely used to detect key crop phenological stages, such as flowering and senescence by analysing dynamics in vegetation indices (Bégué *et al.* 2018). Time series from SAR satellites such as Sentinel-1 can also track vegetation development, even under cloudy conditions (Veloso *et al.* 2017). However, purely observational methods may be affected by noise, missing data, or irregular acquisition times. To improve accuracy, data assimilation can be used by integrating these

satellite-derived observations from RTMs into vegetation models (e.g., STEP, SAFY). This approach corrects model predictions, providing a more reliable estimation of phenological stages.

Despite challenges related to RTM complexity and uncertainty, advances in machine learning, sensor fusion, and high-performance computing are improving their applicability. **Advances and recommendations with respect to RTM Applications** are:

- **Leverage Machine Learning and Deep Learning for Retrievals:** Develop hybrid approaches that combine the physical robustness of RTMs with the data-driven capabilities of ML/DL for parameter estimation and uncertainty reduction.
- **Adopt Multi-Sensor Fusion Strategies:** Combine data from optical, thermal, and radar sensors to enhance RTM-based retrievals.
- **Address Uncertainty in Parameter Estimation:** Incorporate uncertainty quantification methods into RTM workflows to improve the reliability of retrievals. Use probabilistic approaches or ensemble modelling to account for uncertainties in input parameters and model structure.
- **Enhance Field Validation Efforts:** Develop strategies to overcome the scarcity of field data, such as targeted field campaigns or collaborations with local stakeholders but applying sampling protocols dedicated to remote sensing applications (e.g. Elementary Sampling Unit protocols)
- **Tackle Remote Sensing Saturation Issues:** For deeper soil estimates or other parameters prone to sensor saturation, employ indirect modelling approaches. Combine RTMs with ancillary data (e.g., climate, topography) to improve retrievals in saturated regions.

Data assimilation in vegetation or ecosystem modelling involves integrating observational data into process-based models to enhance the accuracy of simulations and predictions while considering uncertainties from the observation and the model predictions. This approach leverages remote sensing based biogeophysical variables to provide timely and spatially extensive data on soil or vegetation conditions, which, when assimilated into models, improve estimations of variables such as biomass, yield, and soil moisture. Direct insertion method which consists in forcing the remote sensing variable shouldn't be considered as an assimilation method even though it was the first natural and intuitive way used in meteorology. Assimilation schemes may include the output of RTM retrievals, which is more commonly used in vegetation modelling assimilation (Trépos *et al.* 2020) or include the RTM model as an observation operator inside the assimilation method (Lievens *et al.* 2016). Various data assimilation approaches have been employed to merge remote sensing data with vegetation or ecosystem models, each presenting unique strengths and challenges (See ORCaSa Deliverable 4.2 for more details).

2.2 MRV methods for forests SOC

Globally, forests occupy about 4.06 billion hectares (ha), representing roughly 31% of the world's land area (FAO, 2020b). The share of land covered by forests varies strongly across regions. In Europe, excluding the UK and Ireland, forest area averages around 35% of total land, while in South America coverage exceeds 45%, largely due to the Amazon basin. In parts of Central Africa and Southeast Asia, forest cover is still above 50%, although declining in some areas due to deforestation. Conversely, in arid and semi-arid regions of North Africa and West Asia, forests occupy less than 10% of land area.

Forests are a major carbon reservoir, with estimates of 668 GtC (FAO, 2020b) or 869.5 Gt C (Pan *et al.*, 2024). These estimates differ because of definitions, assumptions, dataset used. Comparing both

estimates, we can see that dead wood, litter and SOC represents more than half of the total carbon in forests (table 8). Forest SOC (0-1m) represents therefore between 19 to 24% of the global SOC (0-1m) which is estimated to be approximatively 1500 GtC (IPCC 2019, Batjes 1996).

Table 8: Forest carbon pools estimated from Pan et al. 2024 and FAO 2020

Carbon Pool	Pan et al. 2024		FAO 2020	
	(Gt C)	(%)	(Gt C)	(%)
Biomass	371.5	42.7	294.5	44.5
Dead wood + Litter	105.1	12.1	68	10.3
Soil (0-1m)	392.9	45.2	299.5	45.2
Total	869.5	100.0	662	100.0

Forests are managed for a wide variety of purposes, including timber and fuelwood production, protection of water resources, biodiversity conservation, recreation, and increasingly for climate change mitigation. Management systems range from intensive plantation forestry, with short rotations and regular thinning, to low-intensity or unmanaged natural forests where human intervention is minimal.

The carbon balance of forests is influenced by both natural processes (e.g., growth, mortality, and disturbances such as fire, storms, or pests) and management interventions. Harvesting, thinning, or afforestation/reforestation projects alter SOC dynamics directly through soil disturbance and indirectly through litter inputs, root turnover, and woody debris. Consequently, forest SOC is the result of long-term ecological processes and management choices made at stand and landscape scales.

State of the art on forests MRV systems

Integrating Soil Organic Carbon into Forest MRV Frameworks

Soil Organic Carbon (SOC) constitutes a substantial and persistent carbon pool in forest ecosystems, particularly in undisturbed and afforested lands (Batjes et al. 2024). Forest SOC has a significant role in the global carbon cycle through its sequestration potential for climate change. SOC in forest soils contains approximately 45% of the total forest carbon stock, or about 297.9 gigatons (FAO, 2020b). Small variations in these stocks can have considerable impacts on the atmosphere and climate change. Despite its importance, SOC has historically received limited attention in forest MRV systems due to its complex dynamics, deep soil interactions, and slow temporal variability compared to tree biomass (Kimble et al. 2002, Mayer et al., 2020). However, advancements in measurement methods, modeling tools, and carbon accounting standards are progressively enabling more robust integration of SOC into forest carbon assessments (Six et al. 2002, Domke et al. 2017, Brown et al. 2002).

REDD+

(Reducing Emissions from Deforestation and forest Degradation, plus conservation, sustainable management of forests, and enhancement of forest carbon stocks) is a UNFCCC policy framework (Angelsen et al., 2009). It allows developing countries to receive financial incentives for reducing forest emissions and increasing forest carbon stocks (Ochieng et al., 2016). REDD+ provides high-level guidance and principles, but does not itself issue carbon credits. For that, standards and registries have been developed, which operate in voluntary or compliance carbon markets (Cevallos et al., 2019). To be eligible to carbon credit, projects must: demonstrate additionality; set a credible baseline based on historical deforestation, policy drivers and more general land-use trends; implement a robust MRV system; ensure deforestation isn't displaced to another area (leakage); ensure permanence through buffer pools or insurance to take into account the risk of carbon removing (logging, fires,...). REDD+ is progressively shifting toward jurisdictional REDD+ (JREDD): instead of focusing on individual forest projects (e.g., a 10,000-hectare conservation area run by an NGO), the focus is moving toward entire jurisdictions like provinces, states, countries or regions (Boyd et al. 2018; Wang et al. 2025).

Standards like Verra (<https://verra.org/project/vcs-program/registry-system/>), ART (<https://www.artredd.org/trees/>), Gold Standard (<https://www.goldstandard.org/>), and Plan Vivo (<https://www.planvivo.org/>) provide the infrastructure to quantify, verify, and monetize those reductions in the voluntary carbon market (e.g. VM0007 by Verra). These standards align (to varying degrees) with REDD+ principles and IPCC guidance, but operate independently of the UN process (Smith et al. 2020; Forest Carbon Accounting: Overview & Principles <https://www.undp.org/publications/forest-carbon-accounting-overview-principles>; Cevallos et al. 2019; FCPF validation and verification guidelines https://www.forestcarbonpartnership.org/sites/default/files/documents/fcpf_validation_and_verification_guidelines_2021_ver_2.7.pdf). Carbon crediting for forests also exists outside REDD+, and it's a growing part of the voluntary carbon market. While REDD+ focuses specifically on avoided deforestation and degradation (Ochieng et al., 2016), forest carbon credits can also come from other types of activities that are not part of REDD+ (Cevallos et al. 2019). This includes afforestation and reforestation (A/R), improved forest management (IFM), forest restoration or enrichment planting, agroforestry and silvopasture and others more specialized like wetlands, mangrove, urban forestry, etc. Different standards and methods exist for each of these cases (FAO, 2020; Batjes et al. 2024). MRV systems are the technical pillar in both REDD+ and these standards to ensure integrity, transparency, and accountability. MRV systems may have various level of details depending on the project size and adopted standard.

While principles are shared across land-based sectors (Batjes et al. 2024), MRV in forests differs significantly from agriculture and grasslands due to the nature of the carbon pools, spatial scale, and measurement tools (Smith et al. 2020). In forest carbon projects, monitoring should focus on carbon pools defined by the IPCC: Aboveground biomass (trees, branches, foliage), belowground biomass (stump and roots), deadwood (standing or fallen), litter (organic matter on the forest floor), SOC in forest soils (IPCC 2006, 2019). Monitoring of forests has most of the time focused on aboveground biomass estimation, as it is typically the largest pool and most directly impacted by deforestation and degradation. This is eventually complemented with belowground biomass estimations through root-to-shoot ratio (Gibbs et al. 2007). Aboveground biomass may be measured through field sampling

(plot-level tree measurements) and allometric relationships (<https://www.undp.org/publications/forest-carbon-accounting-overview-principles>), and/or through remote sensing with satellite or UAVs (e.g. Mitchell et al. 2017). Remote sensing methods includes different types of sensors (multispectral, LiDAR, radar of different characteristics) and different method analysis (empirical relationships, machine learning, classification models, etc.). Biomass estimation can be structurally complex in function of the type of forest (e.g. primary forest vs. plantations) and must take into account degradation. The monitoring frequency is typically every ~10 years for forest projects, a longer time step compared to cropland or grassland which require more frequent sampling to detect changes. Forests also require leakage monitoring across landscapes which is less relevant in agriculture.

SOC MRV systems for forests

Forests typically have large aboveground and belowground biomass but also significant stocks of litter and Soil Organic Carbon (Kimble et al. 2002). MRV systems for forests have traditionally concentrated on biomass and land-use change emissions, with SOC receiving less attention due to the complex dynamics, depth variability, and slower response times of forest soils resulting in methodological and logistical challenges. As a result, and except for specific cases such as peatland or so-called “blue carbon” in mangroves, SOC have hardly been included in forest MRV methods for carbon stocks accounting (e.g. Gibbs et al. 2007). Agriculture and grassland MRV are more focused on SOC, more temporally dynamic, but also harder to monitor from space compared to forest (which focus more on aboveground biomass).

The IPCC Guidelines (2006, 2019 Refinement) provide high-level recommendations for SOC monitoring under Land Use, Land Use Change and Forestry (LULUCF), but practical implementation varies widely. The FAO’s GSOC-MRV Protocol includes forest land but remains generalist. SOC can be incorporated within existing MRV structures using IPCC Tiered approaches. Tier 1 approaches for forests often rely on default emission factors and carbon stock change factors per forest type and climate region. Tier 2 employs region-specific data, and Tier 3 involves country-specific, repeated measurements and modeling. While Tier 1 and 2 approaches may suit for broad assessments, carbon crediting and REDD+ programs increasingly require Tier 3-level accuracy for SOC. SOC is eligible for accounting under many forest carbon methodologies, especially under afforestation/reforestation, agroforestry or forest restoration. However, most current REDD+ methodologies primarily focus on quantifying avoided emissions from aboveground biomass loss, with limited integration of changes in Soil Organic Carbon (SOC). This is particularly evident in methodologies targeting deforestation and forest degradation, where monitoring efforts are directed toward tree biomass and land cover change, given their more immediate and detectable impacts on carbon fluxes. Similarly, Improved Forest Management (IFM) projects typically emphasize modifications in harvesting cycles, rotation length, and biomass retention. These interventions affect mainly aboveground carbon stocks and residence times, while their influence on SOC dynamics is considered secondary and is often excluded from crediting frameworks. As a result, SOC accounting remains rare in both REDD+ and IFM project types, despite its potential contribution to long-term carbon sequestration.

Compared to cropland, forest SOC MRV needs to integrate a greater depth horizon (typically up to 1 meter), higher natural heterogeneity, and a greater influence of litter layers, root dynamics, and slow turnover processes of lignified materials. Additionally, management impacts are less abrupt and happen more on the long-term (e.g., afforestation, selective logging, fire regimes). Due to longer SOC residence times in forests, SOC changes are slower and require longer monitoring intervals.

Traditional SOC assessment relies on labor-intensive soil sampling and lab analysis, but new proximal sensing tools (e.g. through near infrared or middle infrared spectrometry) and digital soil mapping are improving spatial coverage. Emerging tools such as FullCAM (Australia) or CBM-CFS3 (Canada) include SOC modules for forests, though challenges persist in calibrating forest-specific parameters (e.g., organic layer decomposition, root turnover). These tools treat SOC as a dynamic, integral component of forest carbon budgets. Remote sensing plays a growing role in forest MRV, primarily for aboveground biomass monitoring as mentioned before, but increasingly as a proxy for SOC-relevant indicators (e.g., LAI, litterfall estimations, surface moisture and temperature).

Carbon standards such as Verra's VCS, ART/TREES, Gold Standard and Plan Vivo increasingly incorporate forest SOC accounting, especially in avoided deforestation (REDD+) and afforestation/reforestation (A/R) projects. REDD+, under the UNFCCC framework, typically tracks emissions from deforestation and degradation but is gradually evolving to include soil carbon components, particularly in revised methodological updates (e.g., VM0045 by Verra). Despite this trend, many methodologies still emphasize aboveground biomass and require adaptation to robustly address SOC.

Uncertainty quantification in forest SOC remains underdeveloped compared to croplands, despite the ecosystem's importance in carbon mitigation policies. Standards such as Verra require conservative accounting and uncertainty deduction if confidence intervals are high, requiring MRV systems to improve SOC monitoring precision. Additionally, a strong MRV framework should align with the principles outlined in forest carbon accounting systems: transparency, consistency, comparability, completeness, and accuracy (IPCC, 2006). Forest SOC accounting systems should also ensure permanence, leakage prevention, and additionality, especially under market-based mechanisms like REDD+ and voluntary carbon standards

In the following sections we give a brief overview existing forest MRV systems, with a focus on SOC, and in the Chapter 3.2 we will present some recommendation in ways to improve these systems for forests.

Methods and input for forests SOC MRV

The information in this section complements the deliverable D4.2 on specific information different from cropland, [the D4.2 should be consulted for generic information](#).

2.2.2.1 Spatial and temporal boundaries

Spatial Boundaries: Forest MRV systems for SOC must account for the high natural heterogeneity of forest ecosystems. This includes variation in soil properties, forest types (boreal, temperate, tropical), topography, and management regimes. Forests typically span complex and less accessible terrain compared to arable land, necessitating tailored spatial delineation. Boundaries should encompass the organic layer, mineral soil to at least 30 cm (Tier 1), and ideally to 1-meter depth (Tier 2/3), and may also include litter and deadwood if relevant to the SOC pool. Forest types should be stratified according to species composition, age class, and management history to enhance sampling efficiency and reduce variability.

In forest SOC MRV, leakage refers to displacement of emissions or removals outside the monitored area due to project activities (e.g., intensified harvesting elsewhere). While typically applied to aboveground biomass, leakage may also affect SOC indirectly through changes in land use, soil disturbance, or management practices. Therefore, spatial boundaries must be wide enough to capture such effects. For instance, forest restoration in one region could induce degradation in another due to shifting wood demand. Verra and other carbon standards require leakage risk assessment and, where applicable, deductions from credited emission reductions. However, empirical data on SOC-specific leakage remain limited, highlighting the need for landscape-scale monitoring and research.

Temporal Boundaries: Temporal boundaries are particularly important in forest SOC MRV due to the slow dynamics of soil carbon. SOC changes in forest systems occur over decades, contrasting sharply with croplands where measurable changes can occur within a few years. Therefore, forest SOC MRV typically requires monitoring cycles of 10–20 years. In the past, multiple long-term ecological processes influence forest SOC dynamics, including historical land use, ecological succession, and natural disturbances such as fire, windthrow, and pest outbreaks. Each of these factors can vary significantly in both magnitude and temporal persistence. For example, in boreal forests, wildfire can cause substantial losses of topsoil SOC, with recovery often taking several decades (Palviainen et al. 2020). Conventional logging may have different long-term impact on SOC depending on harvest intensity (Keenan et al. 1993). Short-rotation forest plantations represent a distinct case. Due to their frequent harvest cycles and associated soil exposure, SOC in these systems can be more dynamic and susceptible to decomposition. However, this is partially offset by regular inputs from residual biomass such as stumps, roots, and uncollected branches, and their high productivity (Berhongaray et al. 2017). To fully account for the long-term effects, SOC monitoring in plantation systems must extend across multiple rotation cycles, including phases of replanting or coppicing. Temporal boundaries must also incorporate legacy effects and long-term land-use stability. Forests often retain SOC legacies from past uses (e.g., grazing, agriculture), requiring the use of historical land cover data, disturbance records,

and chronosequence studies to reconstruct SOC baselines and trends. This is in contrast to cropland MRV, where spatial and temporal delineation tends to be more fine-scaled (e.g., plot-level, annual).

Finally, temporal boundaries in MRV systems must be aligned with the permanence requirements of carbon standards. In carbon standards like ART/TREES and Verra, long permanence periods of 30–100 years are targeted, necessitating MRV designs that can sustain temporal coherence, resilience to episodic disturbances, and reliable detection of SOC trends over decades. Plot-level tracking is essential for ensuring traceability, continuity of SOC claims, and the integration of MRV actions across different contexts (e.g., VCM, CAP, NDCs).

2.2.2.2 Setting the baseline

Establishing a SOC baseline in forests differs substantially from croplands due to slower dynamics and more limited direct human intervention. Baselines in forests often require historical reconstruction, particularly for long-standing forest cover, where SOC changes accumulate over decades or centuries. This contrasts with crop systems where baselines can often be linked to recent management shifts. Short-rotation forest plantations fall between these two systems, with long term decomposition of slow-turnover pools, but also frequent (e.g. 5-15 years) clear-cut followed by soil preparation which increases carbon emissions from SOC degradation. Short-rotation forest plantations occupy an intermediate position between these two systems. While they involve regular disturbances such as clear-cutting and soil preparation (e.g., every 5–15 years), which may enhance SOC mineralization, their high productivity and frequent biomass inputs (e.g., roots, stumps, residues) also contribute to long-term carbon accumulation in slower-turnover pools. As such, forest SOC baselines must reflect both disturbance frequency and biomass recycling patterns across multiple rotation cycles.

In most forest carbon projects under REDD+ and Verra, baselines are constructed using historical reference periods, satellite imagery, and national forest inventory data. However, these commonly focus on aboveground biomass and rarely incorporate SOC explicitly. When SOC is included, field measurements or modeled estimates of pre-project SOC stocks, ideally stratified by depth and forest type, are required. Dynamic baselines using Tier 3 process-based models (e.g., RothC, CBM-CFS3) are increasingly employed (Smith et al. 2020; Kurz et al. 2009). These models require careful calibration to local soil, vegetation, and climate conditions, and must be initialized using a "spin-up" approach. Spin-up procedures can assume steady-state conditions or integrate historical land use and land cover transitions, which are particularly important in forests with legacies of grazing, fires, or species changes (Sleeter et al. 2022). SOC baseline can be improved using chronosequences, long-term ecological data, and regionally calibrated forest soil databases. For new afforestation or reforestation projects, default IPCC Tier 1 carbon stock factors may be used as a starting point, but should be refined using local field data or remote sensing proxies if SOC changes are monitored for carbon credit.

Baseline uncertainty is a challenge for all carbon credit projects. Because forest SOC levels vary greatly and data availability is often limited, estimating an accurate starting point is difficult. To address this, carbon standards (e.g. Verra) require a conservative approach: if the baseline estimate is uncertain, project developers must deduct part of the expected carbon benefit to avoid over-crediting.

2.2.2.3 Input data, including remote sensing

Activity: Forest SOC MRV requires input data across multiple ecological layers. Compared to cropland systems, forests demand a stronger focus on natural inputs (e.g., litterfall, root biomass turnover) and less on external inputs (e.g., management practices, fertilizers, tillage). Forest-specific challenges include also deeper rooting systems and heterogeneous organic layers. Input data for forest SOC MRV must incorporate detailed site-specific information on soils, vegetation, climate, disturbances, and management together with the understanding of the soil organisms and the factors that regulate their growth and the maintenance of underground carbon stocks. Data scarcity remains a key issue, especially regarding management. In the following sections, we provide an overview of the input data useful for SOC MRV, with particular emphasis on remotely sensed data sources, which are increasingly being integrated into monitoring frameworks alongside traditional ground-based approaches. While more detailed discussions are provided elsewhere for croplands (Deliverable 4.2) and grasslands (section 2.1.2.6), the focus here is on the specific challenges and requirements of forest applications.

Soil carbon measurements in forests: The precise quantification of forest SOC and its changes presents several challenges, which constitute major obstacles to large-scale sequestration programs (Garsia et al. 2023; Li et al. 2024). Direct measurement of SOC is currently difficult and costly for individual projects. The accuracy of SOC change is even lower, especially at low concentrations of organic carbon in soils (<5% of soil mass). Accurate estimates of SOC remains a major issue for forest MRV, due to both high spatial variability and logistical constraints. Direct measurements involve the assessment of (a) organic carbon concentration in the fine earth fraction (<2 mm), (b) soil bulk density or fine earth mass, and (c) volumetric stone content, especially in coarse-textured or rocky soils (FAO). In forests, additional complexity arises from thick organic layers and coarse woody debris, both of which may contribute to SOC pools but are often omitted or inconsistently sampled. Deep-rooted tree species can redistribute carbon vertically in the soil profile. However, routine monitoring rarely exceeds 30 cm or 1 m depth, leading to systematic underestimation of SOC in deep layers. Remote sensing was shown to enable the estimation of superficial soil organic carbon (SOC) using hyperspectral or multispectral data, provided that the soil surface is visible to the sensor (Gomez *et al.* 2008; Nocita *et al.* 2013). This approach is feasible in croplands, where soil is frequently visible, or sometimes in grasslands. This is rarely the case in forested environments due to canopy cover and ground litter, and because of image resolution limitations (Guo et al. 2023). In forests, soil visibility can occur after harvesting operations that expose the ground, such as clear-cutting. Even in such cases, satellite sensors typically capture the forest floor covered predominantly by litter and harvesting residues, rather than bare soil, and calibration via ground-truthing is essential.

Soil properties: Soil properties are an essential component of SOC accounting, as they influence both the storage capacity and the dynamics of organic carbon stabilization and turnover. Profiles of soil texture, pH, cation exchange capacity, water-holding capacity, influence SOC stabilization mechanisms (e.g., clay content enhances aggregation and protection), decomposition rates, and effective rooting

depth. Data are typically obtained through direct field sampling and laboratory analysis, following standardized soil sampling protocols to ensure consistency and reproducibility.

Global and national geospatial soil datasets are frequently used to complement field measurements, particularly for project stratification or modeling input layers. Examples include SoilGrids (Poggio et al. 2021), GlobalSoilMap (Chen et al. 2022), 'S-World' (Stoorvogel et al. 2017), LUCAS (Ballabio et al. 2016; Ballabio et al. 2019) and FAO-GSP's Global Soil Organic Carbon (GSOC) map (FAO and ITPS, 2018). These resources provide Tier 1-compatible SOC estimates at global to national scale. However, such datasets typically lack the resolution and local specificity needed for Tier 2 and Tier 3 approaches. For instance, DSM products based on machine learning predict SOC using terrain, climate, parent material, and vegetation as covariates, but may not capture fine-scale variability driven by forest microclimates, historical management, or disturbance regimes. Consequently, their accuracy drops significantly at sub-national or project scale.

For Tier 2 approaches, several countries have developed national or regional DSM-based SOC maps using their own soil monitoring data (e.g., Viscarra Rossel et al. 2014, Ballabio et al. 2019). While suitable as regional baselines, they are often based on SOC data spanning decades, or rely on mixed lab methods and varying sampling depths, reducing their suitability for Tier 3 modeling or project-level crediting.

Vegetation characteristics: Vegetation characteristics directly affect SOC inputs through the continuous deposition of litterfall, root turnover, and rhizodeposition. In the context of MRV systems under carbon standards such as Verra's VCS or ART/TREES, detailed quantification of these processes is not typically required. However, vegetation data play a crucial indirect role by informing estimates of productivity and biomass turnover, which influence SOC modeling and stock change assessments (Chiti et al. 2024). Standard carbon accounting methods generally rely on field-based biomass inventories, national forest inventory data, and remote sensing products to estimate forest structure and productivity. Key vegetation variables include species composition, stand age, and canopy cover, which can be used to stratify sampling efforts or to support empirical SOC models. Remote sensing data from LiDAR, radar or multispectral sensors provide valuable information on canopy height, crown area, and vegetation density, which may serve as proxies for carbon inputs to the soil. Various methodologies exist to estimate vegetation properties from remote sensing (e.g. Tian et al. 2023, Mthembu et al. 2023, Xu et al. 2020). The approaches developed for croplands (D4.2) or grasslands (2.1.2.6) remain applicable for forest canopies, but require adaptation to account for forest specificities. While some principles remain applicable, such as the use of spectral indices or radiative transfer model (RTM) inversion, forest canopies exhibit distinct challenges that necessitate adapted methods. First, woody biomass represents a central characteristic which needs dedicated methodologies in forest, mainly using active sensors such as LiDAR or SAR (Tian et al. 2023). The structural heterogeneity of canopies, including vertical gradients, canopy foliage clumping, mixed species composition, complicates RTM inversion, and often requires developing specific methods and models (Verrelst et al. 2015). Finally, saturation effects in optical vegetation indices (e.g., NDVI) are more pronounced in dense forests, limiting their capacity to capture variation in high-biomass stands. Addressing these limitations requires the integration of multi-sensor observations and the development of forest-specific retrieval models that explicitly account for canopy structure and woody components (Mutanga et al. 2023). Leaf Area Index (LAI), although not a mandatory metric in most

carbon accounting methodologies, can support SOC estimation by serving as an indirect proxy for net primary productivity (NPP). Since NPP governs litter and root biomass inputs to the soil, LAI-derived estimates can inform Tier 3 SOC models, especially when calibrated to local forest conditions. When integrated with simplified allocation assumptions, LAI-derived estimates can improve the estimation of carbon inputs from litter and root biomass, particularly in Tier 3 modeling frameworks. However, the use of such dynamic proxies requires site-specific calibration and is generally reserved for advanced MRV systems. Inputs such as branch turnover, coarse woody debris, and fallen trees are often not directly quantified in carbon standards but may be approximated using biomass turnover rates or included in Tier 3 process-based models (e.g., CBM-CFS3, FullCAM). These components can significantly influence long-term SOC sequestration, especially in mature or unmanaged forests.

Climate data: Temperature, precipitation, and radiation strongly influence SOC dynamics by regulating plant productivity, microbial activity, and organic matter decomposition. Tier 3 models (e.g., RothC, CENTURY, DayCent) require consistent long-term weather inputs for initialization and simulation, typically including monthly or daily temperature, rainfall, and evapotranspiration (Coleman & Jenkinson, 1996; Parton et al., 1987; Del Grosso et al., 2002). As mentioned earlier in this document (section 2.1.2.6) or in the deliverable D4.2, methods exist to estimate soil moisture from microwave sensors. Estimating soil moisture remotely within forested ecosystems is inherently challenging due to interference from overlying vegetation and litter layers. While microwave-based remote sensing (e.g., SAR or passive microwave) can infer surface moisture, forest canopy and biomass (litter and residues on the forest floor) significantly attenuate and complicate the received signal (Chen et al. 2021). In such contexts, integrating remote observations with ground-based measurements is essential to ensure accuracy across heterogeneous forest conditions (Yu et al. 2023).

Disturbance data: In existing forest MRV systems, data on past disturbances have increasingly been integrated into carbon accounting frameworks, particularly at the national and jurisdictional levels. Historical disturbance data are used primarily to improve baseline setting, model initialization, and to capture legacy effects crucial for accurately simulating SOC dynamics. For instance, Canada's National Forest Carbon Monitoring, Accounting, and Reporting System integrates historical fire, insect outbreak, and harvest data into the CBM-CFS3, which explicitly models carbon stock changes from such disturbances (Kurz et al. 2009). Similarly, Australia's Full Carbon Accounting Model (FullCAM) routinely incorporates historical land-use and disturbance data, such as clearing events and fire history, to accurately represent past carbon dynamics and inform annual carbon budgets (Richards & Evans, 2004). Remote sensing is a powerful tool for monitoring forest disturbances across large spatial and temporal scales (Soubry et al. 2021). Satellite observations allow the detection of events such as wildfires, insect outbreaks, storms, and logging, which would be difficult to capture consistently through field surveys. Optical sensors like Landsat and Sentinel-2 provide time-series data that enable the identification of disturbance patterns and canopy openings, even at relatively fine spatial resolution (Fekety et al. 2025). At broader scales, sensors such as MODIS offer dense temporal coverage for tracking vegetation stress and fire scars in near real time (Baccini et al. 2017). Advances in active remote sensing, particularly LiDAR from missions such as GEDI, further improve disturbance

monitoring by quantifying structural changes in canopy height, gap fraction, and biomass (Dubayah et al. 2020). In addition, operational platforms like ForWarn (<https://forwarn.forestthreats.org/>) integrate multi-sensor data to provide early warnings of insect or disease outbreaks, detecting anomalies in forest greenness before they are evident on the ground. Together, these approaches demonstrate how remote sensing supports the detection, attribution, and monitoring of forest disturbances in a consistent and scalable way.

Forest management practices: Unlike croplands, where activity data such as tillage or fertilization are often logged, forest management data tend to be less systematically recorded and spatially explicit datasets are scarcer. Yet, detailed information on forest operations for managed forests, such as thinning intensity, clear-cutting extent and frequency, soil preparation methods in plantations (e.g., plowing or ripping), and replanting cycles, is crucial for estimating SOC inputs and turnover. Additional practices like residue handling (e.g., whether branches, stumps, or litter are left on site, removed, mulched, or burned) or application of organic or mineral fertilizers, though less frequent in forest settings, can influence SOC stocks, especially in plantation systems. Remote sensing optical data can be used for detecting forest management practices, such as clear-cutting, selective logging, thinning, and planting can be identified through spectral and temporal change analysis, often with high reliability when dense time series are available (Fassnacht et al. 2023).

2.2.2.4 Decision support tools

Decision Support Tools and Process Models for forest SOC MRV

Decision Support Tools (DSTs) play a central role in operationalizing MRV systems for forest carbon accounting. Traditionally, these tools have focused on aboveground biomass, forest cover change, and carbon stock assessments aligned with REDD+ and voluntary standard methodologies. Examples include Tier 1 tools such as the FAO's EX-ACT (<https://www.fao.org/tc/exact/ex-act-home/en/>) and the Cool Farm Tool (<https://coolfarm.org/>), which provide rapid assessments based on IPCC default factors; Tier 2 tools like CO2FIX (<https://efi.int/knowledge/models>), which allow more regionally tailored forest carbon estimates including soil; and Tier 3 platforms such as Canada's CBM-CFS3 and Australia's FullCAM, which integrate detailed forest growth, disturbance, and soil modules at spatial resolutions suitable for national GHG inventories and project-level reporting. FullCAM supports spatial resolutions as fine as 25 m and CBM-CFS3 can be calibrated with forest inventory data and disturbance history inputs. These platforms vary in ease of use and input complexity, with Tier 3 systems requiring detailed site-specific data but offering greater accuracy for SOC simulation and carbon accounting. These tools have proven effective for aboveground carbon pools, deadwood, and litter, but many either lack integrated SOC modules or treat SOC in a simplified, static manner. For DSTs to fully support SOC integration, they must transition from biomass-centric designs toward comprehensive multi-pool carbon accounting systems. This involves adding or enhancing modules that account for soil depth profiles, carbon input from litter and roots, decomposition rates, and disturbance impacts. Process-based models such as RothC, CENTURY, and Yasso provide established frameworks for modeling SOC turnover and sequestration (e.g. Peltoniemi *et al.* 2007). When combined or integrated with forest-specific DSTs, they enable more robust simulations of how SOC responds to various forest

management practices and ecological conditions. In advanced implementations, these tools are calibrated using region-specific parameters, historical land use data, and localized climate information.

As recommended in cropland systems, DSTs should ideally allow project developers and land managers to simulate multiple forest carbon management scenarios (e.g., afforestation, extended rotations, residue management) and estimate the relative SOC gains or losses. Similar to tools like SIMEOS-AMG (<http://www.agro-transfert-rt.org/ressources/simeos-amg-2/>) or COMET-Farm (<https://comet-farm.com/>) used for arable land, forest-oriented DSTs should offer scenario testing capabilities tied to practical decisions and ideally balancing environmental, economic, and social criteria. A critical improvement would be the integration of dynamic remote sensing inputs (e.g., LAI, NDVI, biomass) to inform real-time vegetation status and SOC modeling inputs—an approach already being implemented in cropland-focused platforms like EO4AGRI or models assimilating Sentinel and Landsat data.

Updated versions of FullCAM and CBM-CFS3 now include SOC modules that simulate the effects of afforestation, reforestation, selective logging, and natural disturbances (e.g., fire, windthrow). ORCHIDEE, a land surface model developed in Europe, incorporates SOC dynamics within a broader ecosystem carbon budget, integrating vegetation, soil, and climate interactions. This model is a research model and not a DST, but it provides critical process understanding and calibration data for tools that are used in MRV and give valuable foundations to enhance or validate DST SOC modules. These advanced platforms rely on empirical datasets, region-specific calibration, and long-term monitoring to improve accuracy. Participatory tools enabling stakeholder involvement (e.g., forest managers, indigenous communities) are also emerging, aligning with REDD+ safeguards and ensuring DSTs reflect local practices and priorities. This reinforces MRV legitimacy and enhances usability and acceptance.

Support Platforms and MRV Systems for forest SOC MRV

Open platforms such as the REDD+ Monitoring Portal (<https://redd.unfccc.int/>), Open Foris (<https://openforis.org/>), and Silvacarbon (<https://www.silvacarbon.org/>) provide additional infrastructure for MRV implementation, training, and transparency. While none of these platforms natively model SOC, they can support SOC integration by collecting field soil data within national forest inventories, linking outputs to external SOC models (e.g., RothC, CENTURY), or embedding SOC functionality via interfaces like SEPAL or custom data modules. Following cropland MRV best practices, these platforms should expand to allow direct upload of in-situ soil, management, and climate data and interface with decision support tools. The possibility to use standardized vocabularies (e.g., AGROVOC), harmonized input formats (e.g., CSV, GeoJSON), and uncertainty tracking (e.g., for bulk density, SOC concentration) would also strengthen their reliability and interoperability.

Emerging digital MRV (dMRV) platforms aim to bridge existing gaps by automating data processing pipelines and incorporating remote sensing-derived proxies (e.g., vegetation indices, biomass estimates, canopy cover) relevant to carbon accounting. Examples include Pachama (<https://pachama.com/>), Upstream Tech (<https://www.upstream.tech/>), and NCX (<https://ncx.com/>), but except for Upstream Tech which relies on COMET-farm, the SOC is not accounted for. Compared to cropland systems, dMRV in forests remains more focused on land cover change and aboveground

biomass estimation. To fully integrate SOC, forest dMRV systems should enable ingestion of site-specific SOC observations and model outputs, track litter and root inputs using remote sensing proxies (e.g., LAI), and apply spatial stratification strategies to reduce uncertainty. These features are essential for building credibility in carbon markets and aligning dMRV platforms with Tier 3 IPCC methodologies.

3 Recommendations on methods for monitoring SOC

3.1 Grasslands

Adapted MRV approaches appear necessary to capture the full complexity of soil organic carbon (SOC) dynamics in pasture-based livestock systems in the three components of MRV: monitoring, reporting, verification. Overall, advancing towards integrative, multi-ecosystem MRV systems will be a decisive step for recognising the mitigation potential of pasture-based livestock systems, while simultaneously strengthening their role in adaptation and sustainable development strategies.

Applying UNFCCC TCCCA (Transparency, Comparability, Consistency, Completeness, Accuracy) for SOC MRV in livestock system is essential to monitor SOC stock changes in grasslands, rangelands, and silvopastoral systems, which are heterogeneous and sensitive to management, climate, and land-use change. Ensuring TCCCA strengthens the credibility of livestock-related mitigation outcomes in NDCs, improves access to climate finance, and supports integration of mitigation and adaptation at national and territorial levels.

To build adapted MRV approaches, integrative approaches that combine reliable measurement protocols, adapted modelling tools, and participatory monitoring are essential for accurately assessing SOC dynamics in livestock-based systems. Decision support models thus play a dual role: (i) providing ex-ante estimates of SOC sequestration potential of livestock-related interventions (e.g., rotational grazing, reseeded with legumes, silvopastoral systems), and (ii) generating ex-post accounting compatible with MRV requirements for NDCs and carbon crediting schemes.

3.1.1. Integration of approaches and systems diversity

This document provides recommendations for building an integrative and multi-ecosystem MRV framework tailored to livestock landscapes. It emphasizes ecosystem-based stratification, long-term monitoring, integration of Earth Observation (EO) with ground data, and participatory approaches that leverage local pastoral knowledge in tropical livestock landscapes.

The design of robust MRV frameworks must therefore integrate livestock-specific activity data—such as stocking rates, grazing calendars, mobility patterns, and manure management practices—into SOC monitoring models. This integration is critical for reducing uncertainties in SOC accounting, capturing

management-induced effects, and ensuring the applicability of MRV systems across the diversity of livestock landscapes.

Integration is essential: Robust SOC MRV frameworks must combine multiple approaches—direct measurements, modelling, remote sensing, and participatory methods—adapted to local contexts.

MRV systems should stratify landscapes according to climatic gradients especially in tropical area (humid vs. arid/semi-arid), management systems (communal vs. ranching), and soil types. For instance:

- Humid tropical grasslands (e.g., Brazilian Cerrado, East African savannas) require high-resolution monitoring of biomass turnover, fire dynamics, and manure deposition.
- Tropical specificity must be addressed: Tropical grasslands and rangelands, where livestock systems dominate, require tailored methodologies that capture particularly heterogeneity, depth of SOC storage, and vulnerability to climatic variability.
- Arid and semi-arid rangelands (e.g., Sahel, Horn of Africa, northern Australia) require long-term SOC monitoring across transhumance corridors, fall-back zones, and degraded patches where carbon fluxes are highly variable.

Diversity of livestock management practices calls for locally determined baselines and adapting MRV systems for the diverse types of livestock systems. SOC baselines, in particular, should integrate the typologies of grazing systems. For example, for tropical systems sedentary livestock farming systems, agro-silvopastoral, transhumant, nomadic systems should be distinguished.

For transhumant and nomadic pastoral systems, historical and participatory data on land use can be based on the knowledge of pastoralists. In the absence of historical data, counterfactual scenarios can be developed using Earth observation archives (e.g. Landsat, MODIS) combined with livestock census data.

3.1.2. Soil sampling

Croplands and pastures show contrasting patterns of Soil Organic Carbon (SOC) storage, with direct implications for SOC dynamics and monitoring (cf 2.1.2). Pasture systems often accumulate substantial SOC in deeper horizons, underscoring the need for MRV frameworks that extend beyond surface sampling. Incorporating multi-depth measurements is therefore essential to accurately assess both the sequestration potential and the permanence of SOC in grazing-based systems.

These differences imply that pastures demand multi-depth sampling and spatially explicit monitoring to capture heterogeneity and the influence of grazing patterns. Thus, while croplands present opportunities for SOC improvement through conservation agriculture, sustainably managed pastures represent more resilient and deeper carbon reservoirs, making their integration into MRV frameworks particularly critical for accurate NDC reporting.

Table 9: Soil sampling differences between Croplands and pastures, implications and recommendations for grasslands and rangelands.

Dimension	Croplands	Pastures (Grasslands & Rangelands)	Direct Implications for SOC Dynamics & Monitoring (MRV)
SOC distribution	More concentrated in topsoil (0–30 cm) ; vulnerable to disturbance.	SOC extends into deeper horizons (up to 1 m) under permanent grasslands.	MRV in croplands requires frequent shallow sampling ; in pastures, multi-depth sampling is essential.
Land-use legacy	Conversion from forest/grassland → large SOC losses (≈15–30%). Recovery possible but slow.	Conversion from forest → initial losses; well-managed pastures can partially restore SOC.	MRV baselines must integrate land-use history (deforestation, cultivation cycles, pasture renewal).
Carbon inputs	Depend on crop residues, rotations, fertilisers ; inputs seasonal and often removed.	Continuous root turnover, litter deposition, and manure return from grazing animals.	MRV must track management practices in croplands vs. organic inputs and grazing patterns in pastures.
Stability of SOC	Gains are fragile, requiring continuous inputs and conservation practices.	SOC stocks more stable and resilient if pastures are not degraded.	Pastures offer longer-term sequestration potential ; croplands more prone to reversal.
Vegetation type	Mostly annual crops; low root biomass compared to grasses.	Perennial grasses (C3/C4), legumes; higher root biomass and deeper rooting systems.	MRV must account for functional types (C3/C4, legumes) in SOC modelling and monitoring.
Degradation risks	Tillage, erosion, residue burning, monocropping.	Overgrazing, fire, erosion, land degradation.	MRV must include risk assessment indicators (erosion, grazing pressure).
Knowledge base	Long history of field trials and experiments in temperate croplands.	Less long-term data in tropical pastures, especially under pastoralism.	Strong need for capacity building, Tier 2/3 factors in tropical pastures.

3.1.2 Other data acquisition methods

Temperate grasslands have often been established since a long time and are mainly located in countries with records included in either crop production or livestock production activity data. Tropical pasture-based livestock systems display distinct characteristics compared to their temperate counterparts, with significant implications for Soil Organic Carbon (SOC) dynamics and monitoring. These specificities underscore both the challenges of establishing effective MRV frameworks in tropical contexts and the considerable—but highly vulnerable—potential of these systems to contribute to carbon sequestration. Therefore, targeted recommendations are needed to strengthen the robustness of SOC estimates and to ensure the long-term permanence of sequestration.

Table 10: Data acquisition in temperate and tropical pastures, implications and recommendations for grasslands and rangelands

Dimension	Tropical Livestock Systems (Grasslands & Rangelands)	Temperate Livestock Systems (Grasslands & Pastures)	Implications for MRV of SOC
Land-use history	Strongly linked to deforestation and land conversion (e.g., Amazon, Central Africa). Initial SOC losses followed by partial recovery if pastures are maintained & well managed.	Generally long-established pastures, less tied to deforestation history. SOC stocks relatively stable.	Need to capture land-use legacy (deforestation vs. pasture renewal) in SOC baselines.
Vegetation types	Dominated by C4 grasses ; SOC increases when C3 legumes/shrubs are integrated (better N inputs).	Dominated by C3 grasses ; SOC dynamics more dependent on grazing intensity & fertilizer use.	MRV must account for C3–C4 interactions and species composition in tropics.
Climate & stressors	High variability: droughts, erratic rainfall, fire regimes. SOC stocks fragile & heterogeneous.	More stable climates, lower inter-annual variability, less fire pressure.	MRV frameworks need to integrate climate variability & fire impacts in tropical regions.
Grazing systems	Predominantly extensive, communal, mobile (ranching, pastoralism, transhumance) . Creates spatial heterogeneity in SOC (water points, corridors). But also grazing rotational system.	Predominantly sedentary, intensive or rotational grazing in private farms. SOC changes easier to attribute to management. But also, extensive system including transhumance and nomadism in Asian step.	Tropical MRV must use spatially explicit, landscape-scale approaches (EO + participatory monitoring).
SOC vulnerability	Higher risk of rapid losses due to overgrazing, land-use change, temperature increases.	More stable SOC stocks; vulnerability mainly from tillage, land conversion, or over-fertilization.	SOC permanence is a major concern in tropical MRV; requires risk assessment and uncertainty tracking .
Knowledge gaps	Few long-term studies; limited systematic SOC assessments in Africa, Amazon, Asia.	More extensive data, long-term experiments available (Europe, North America).	Tropical MRV needs capacity building, long-term monitoring, and region-specific factors (Tier 2/3) .

3.1.3 Modelling SOC stock changes

Process-based soil models such as RothC, CENTURY, and DayCent simulate SOC dynamics by integrating carbon inputs from pasture biomass, litter, and livestock residues, as well as SOC decomposition and interactions with climate and soil type. These models are widely used in FAO protocols and national MRV frameworks, and have been successfully calibrated for temperate pastures

(FAO, 2019; FAO, 2020a). However, their performance depends strongly on the quality of input data, including biomass production, litter inputs, and residue returns, variables that are often difficult to obtain at the farm scale due to limited farmer records and high measurement costs.

On the other hand, fully coupled plant–soil models provide more mechanistic simulations of vegetation–soil interactions, but are even more demanding in terms of input data and parameterization. This dependency on complex datasets is particularly challenging in tropical grasslands, where spatial heterogeneity is high and SOC dynamics extend beyond surface soils. Strengthening SOC MRV in these systems therefore requires both (i) the calibration of process-based models with local data, and (ii) the development of pragmatic approaches to simplify or approximate biomass and residue inputs while maintaining model accuracy.

Hybrid approaches that combine measurement with model calibration are increasingly recommended by World Bank (2021) and FAO (2021). Lavalée et al (2024) highlights that consistent workflows for model initialization, calibration, and validation are critical for ensuring credibility, as model outputs can diverge widely depending on assumptions.

Empirical/statistical models (e.g., IPCC Tier 1/2 factors, look-up tables) are still used for large-scale inventories where data is scarce. However, their applicability is limited in rangelands due to high variability in grazing intensity, fire regimes, and rainfall. Most Tier 1-2 tools lack the accuracy needed for economic decisions such as subsidy allocation, cost-effectiveness evaluation of climate solutions, or carbon credit certification, due to high uncertainties at field or farm scales. Even Tier 3 models, despite their detailed simulations, remain sensitive to input data variability, aggregation issues, and internal model errors. While Tier 1-2 approaches can deliver results comparable to Tier 3 models, they do so with wider uncertainty. Consequently, most tools still require expert users or advisor-friendly interfaces, complemented by training and long-term technical support. In practice, Tier 1-2 models are more appropriate for action-based payments than for impact-based compensation, since they indicate trends rather than precise emission changes. At larger scales, farm diversity may help average out errors, provided that the sampling strategy captures the variability of the wider farming landscapes.

3.2 Forests

Monitoring SOC in forest ecosystems differs markedly from cropland due to slower dynamics, deeper carbon pools, and limited direct management interventions. These differences affect the selection of sampling protocols, data sources, modeling approaches, and MRV system design. The following recommendations address key aspects of SOC monitoring in forests based on current knowledge and the insights previously discussed in Section 3.

3.2.1 Spatial and temporal boundaries

Spatial boundaries for SOC monitoring should explicitly address forest-specific complexities by incorporating detailed stratification approaches based on forest type, management regime, disturbance history, and soil characteristics. Boundaries should include deeper soil layers, typically

extending to at least 1 meter for Tier 2 and Tier 3 methodologies, as well as aboveground litter and coarse woody debris when these components contribute significantly to SOC pools. It is recommended to adopt flexible spatial stratification that can dynamically reflect disturbances or changes in land management over space and time, in particular to avoid or take into account possible leakage.

Temporal boundaries must consider the inherently slower and longer-term dynamics of forest SOC compared to agricultural systems. SOC monitoring intervals should typically range from 10 to 20 years, aligning with forest management cycles and natural regeneration processes. Monitoring designs should incorporate historical data and chronosequences to accurately represent long-term legacy effects of past disturbances or management practices. Permanence periods required by carbon standards (30–100 years) should inform the design and planning of SOC monitoring activities to ensure temporal consistency and accurate detection of SOC stock changes. Unlike in agricultural systems where annual plot-based SOC assessments are increasingly common (e.g., under the CAP or CRCF), forest SOC MRV relies on decadal or multidecadal continuity, and less frequently includes result-based mechanisms. Nonetheless, similar principles apply: spatially explicit monitoring units (e.g., parcels, compartments), continuity post-project (to verify long-term carbon benefits), and harmonization across MRV systems can strengthen credibility and prevent double counting. These features become particularly relevant as convergence grows between voluntary carbon markets and regulatory frameworks.

3.2.2 SOC baseline

Compared to cropland MRV, forest SOC baselines tend to be less temporally granular and less standardized. While agricultural systems increasingly explore result-based payments tied to annual SOC changes, forest systems often require conservative, long-term projections under business-as-usual conditions. This underscores the need for robust historical data, region-specific models, and permanent plot monitoring to ensure environmental integrity and credibility in forest-based carbon crediting.

To increase trust and credibility in SOC baselines, it's also essential to involve local stakeholders and rely on high-quality, peer-reviewed regional data. This ensures that assumptions and data sources are transparent, consistent, and scientifically sound. MRV systems should also document all assumptions, sampling methods, and model parameters used to develop baselines (Griscom et al., 2020). Harmonizing baseline development with national MRV systems and ensuring transparency across verification cycles will be essential as forest carbon methodologies converge with broader land-sector accounting frameworks (e.g., CRCF, CAP, or national NDCs).

3.2.3 Soil sampling and soil data

Direct soil sampling remains the most reliable method for SOC quantification in forests. To effectively capture forest-specific SOC dynamics, soil sampling protocols should explicitly include greater sampling depths, typically extending at least to 1 meter for Tier 2 and Tier 3 applications, due to deeper rooting systems and less frequent disturbance. Field campaigns should systematically incorporate assessments

of litter and coarse woody debris (CWD), as these significantly contribute to forest SOC pools. Where feasible, field campaigns should also include sampling points near stumps or dead trees. Given the high spatial heterogeneity inherent to forest soils, enhanced sampling density or carefully planned spatial stratification is recommended. This can be achieved by using stratification based on vegetation types, management regimes, soil properties, and disturbance history. Bulk density, stone content, and organic horizon thickness should always be measured to ensure accurate SOC stock calculations. Due to practical challenges and costs, hybrid approaches combining direct soil measurements with modeled or literature-derived parameters are recommended when resources or access are limited.

Chronosequences and paired-site studies can provide indirect assessments of long-term changes. Geospatial soil datasets (e.g., SoilGrids, LUCAS, national inventories) are increasingly used to complement sparse field data, but verification with local sampling remains necessary, particularly for Tier 2 and 3 methodologies.

Following best practices from cropland MRV, soil properties should be measured at consistent depth intervals (e.g., 0-30 cm, 30-60 cm, 60cm-1m) and using harmonized protocols, particularly when Tier 3 modeling is applied. Consistency in lab methods, sampling time (e.g., post-harvest or post-disturbance), and standard units is essential for comparability and transparency.

Where feasible, project developers should prioritize recent, harmonized, and geo-referenced soil data collected using consistent depth intervals (e.g., 0–30 cm or 0–100 cm), bulk density methods, and lab protocols. In forests, this also includes the organic horizon. A promising innovation for bridging gaps between mapped and measured data is the use of space-time digital soil mapping and data fusion with process-based models (e.g., Ugbemuna Ugbaje et al. 2024). These approaches aim to dynamically update soil maps using new observations and model feedbacks, thereby increasing their relevance for MRV systems operating under Tier 3 requirements.

In practice, the inclusion of soil data depends on whether the project is applying a Tier 1, 2, or 3 approach per IPCC guidelines. For Tier 1 methodologies, default SOC values and emission factors from the IPCC or national GHG inventories may suffice. In Tier 2 or 3 approaches, spatially explicit soil maps and chronosequence data are often used to estimate pre- and post-project SOC stocks, or to parameterize process-based models such as RothC or Century. In such cases, the additional soil descriptors, such as water-holding capacity, cation exchange capacity, and horizon-specific SOC, may enhance model performance, but they are not mandated (e.g. Verra or REDD+) unless explicitly stated in a methodology (e.g., peatland modules under VM0007). To align with FAIR data principles (Findable, Accessible, Interoperable, and Reusable), soil data sources used for SOC MRV should be well-documented, publicly accessible when possible, and traceable to their origin. Initiatives to harmonize legacy and contemporary soil data (e.g., Batjes et al. 2024; Cornu et al. 2023) offer a pathway to strengthen the evidence base for forest SOC monitoring, especially in countries lacking robust soil monitoring infrastructure.

3.2.4 Other data

Climate data: High-resolution climate datasets from sources like WorldClim or ERA5 help model to integrate these effects over time but may miss local heterogeneity, especially under forest canopy.

Some satellite products may also inform on surface moisture or surface temperature, with the difficulty to give reliable information on these soil properties because of the presence of the forest strata (See section 3.2.2.3). Local weather station data, where available, should be integrated to validate or refine gridded datasets (Webb et al., 2020). Super-resolution techniques and remote sensing assimilation into ecosystem models are promising for downscaling and improving weather inputs (Padarian et al., 2022; Wijmer et al., 2024; Smith et al., 2020).

Disturbance data: Past and recent disturbance data are essential for accurate SOC MRV in forests, as events such as wildfires, logging, insect outbreaks, and windthrow can significantly alter soil carbon inputs and decomposition processes. High-resolution and temporally consistent datasets have been recently produced which are useful for detecting and quantifying these disturbances. The JRC Sentinel-2 Platform for REDD+ provides near-real-time canopy disturbance detection at 10 m resolution with ~5-day revisit, while the JRC Tropical Moist Forest (TMF) dataset offers detailed classification of forest degradation and deforestation since 1990 at 30 m resolution, based on Landsat time series (<https://forobs.jrc.ec.europa.eu/>). Global Forest Watch (GFW) publishes annual 30 m tree cover loss maps from 2001 onward (<https://www.globalforestwatch.org/>), and its GFW Drivers layer classifies causes of loss, such as wildfire, logging, and shifting agriculture, at 1 km resolution. National-level programs also provide critical data: Canada's National Forest Inventory includes harvest and disturbance statistics (<https://nfi.nfis.org/>), while Brazil's PRODES system delivers annual Amazon deforestation maps at 30 m for areas >6.25 ha (<https://www.obt.inpe.br/>). For biotic disturbances, a harmonized database of over 676,000 insect and disease events across Europe from 1963 to 2021 was developed (Forzieri et al. 2023). The Global Land-Use Harmonization dataset (LUH2) offers gridded historical and future land-cover transitions (1700–2100) at 0.25° resolution, useful for model initialization and spin-up procedures (<https://luh.umd.edu/>). These datasets illustrate the diversity of available sources existing to support both recent and legacy disturbance quantification, enabling Tier 2 and 3 SOC modeling across scales.

Forest management practices: As in cropland MRV, the use of standardized nomenclatures (e.g., ISO or IPCC land use categories) and structured metadata collection enhances data consistency. Verification by third parties such as national forest inventories, forest agencies, or certification schemes (e.g., FSC, PEFC) can improve data reliability, particularly when forest management records are missing. Participatory mapping, community forest monitoring, and integration with forest concession or certification databases offer practical solutions for filling activity data gaps, and are increasingly supported by tools such as Collect Earth Online or the FAO's Open Foris suite (<https://openforis.org/>). These approaches can facilitate more transparent, spatially explicit, and verifiable documentation of forest practices, which are essential inputs for Tier 2 and Tier 3 SOC monitoring approaches.

Integration and harmonization: To meet Tier 2 or 3 standards, input datasets should be georeferenced, harmonized across spatial scales, and regularly updated. Where direct data are unavailable, proxies or modeled estimates may be used, but their assumptions and uncertainties must be transparently documented. Integration of field data, remote sensing, and GIS layers enables scalable SOC assessments that are consistent with IPCC guidelines and compatible with other land-sector MRV systems (e.g., CAP, CRCF). Compared to cropland MRV—which emphasizes granular, often annual data from farm management systems—forest SOC MRV relies more heavily on ecological

proxies, chronosequences, and geospatial data, underscoring the importance of site-specific calibration and robust model initialization.

3.2.5 Modelling SOC stock changes

Given the complexity and slower temporal dynamics of forest ecosystems, it is essential to use models explicitly designed for long-term SOC dynamics. Process-based models such as CENTURY, CBM-CFS3, FullCAM, and Yasso are recommended for their detailed representation of litter pools and decomposition processes, particularly important in forests. These models require careful initialization or spin-up procedures, utilizing historical land-use, disturbance, and climate datasets to accurately represent past SOC conditions. It is recommended to use global datasets (e.g., LUH2, GFW, TMF) and integrate them with local forest histories and management records for effective model initialization. This approach ensures that legacy effects, critical in forests due to their long-term impact on SOC, are adequately captured.

Few **Decision Support Tools (DSTs)** described in section 3 includes integrated SOC modules (e.g. CBM-CFS3). For DSTs to fully support SOC integration, they must transition from biomass-centric designs toward comprehensive multi-pool carbon accounting systems. This involves adding or enhancing modules that account for soil depth profiles, carbon input from litter and roots, decomposition rates, and disturbance impacts. Process-based models such as RothC, CENTURY, and Yasso provide established frameworks for modeling SOC turnover and sequestration (e.g. Peltoniemi et al. 2007). When combined or integrated with forest-specific DSTs, they enable more robust simulations of how SOC responds to various forest management practices and ecological conditions. In advanced implementations, these tools can be calibrated using region-specific parameters, historical land use data, and localized climate information.

As recommended in cropland systems, DSTs should ideally allow project developers and land managers to simulate multiple forest carbon management scenarios (e.g., afforestation, extended rotations, residue management) and estimate the relative SOC gains or losses. Similar to tools like SIMEOS-AMG (<http://www.agro-transfert-rt.org/ressources/simeos-amg-2/>) or COMET-Farm (<https://comet-farm.com/>) used for arable land, forest-oriented DSTs should offer scenario testing capabilities tied to practical decisions and ideally balancing environmental, economic, and social criteria. A critical improvement would be the integration of dynamic remote sensing inputs (e.g., LAI, NDVI, biomass) to inform real-time vegetation status and SOC modeling inputs—an approach already being implemented in cropland-focused platforms like EO4AGRI or models assimilating Sentinel and Landsat data. To overcome limitations posed by canopy coverage, a recommended strategy is combining targeted ground-truth sampling with advanced remote sensing technologies, such as LiDAR and radar, and mobile proximal sensing technologies (e.g., near-infrared spectroscopy). This integration can improve the spatial representation of SOC variability and enhance model calibration and validation.

Support platforms and dMRV systems for forest SOC MRV: Open platforms such as the REDD+ Monitoring Portal (<https://redd.unfccc.int/>), Open Foris (<https://openforis.org/>), and Silvacarbon (<https://www.silvacarbon.org/>) provide additional infrastructure for MRV implementation, training, and transparency. While none of these platforms natively model SOC, they can support SOC integration

by collecting field soil data within national forest inventories, linking outputs to external SOC models (e.g., RothC, CENTURY), or embedding SOC functionality via interfaces like SEPAL or custom data modules. Following cropland MRV best practices, these platforms should expand to allow direct upload of in-situ soil, management, and climate data and interface with decision support tools. The possibility to use standardized vocabularies (e.g., AGROVOC), harmonized input formats (e.g., CSV, GeoJSON), and uncertainty tracking (e.g., for bulk density, SOC concentration) would also strengthen their reliability and interoperability. Emerging digital MRV (dMRV) platforms aim to bridge existing gaps by automating data processing pipelines and incorporating remote sensing-derived proxies (e.g., vegetation indices, biomass estimates, canopy cover) relevant to carbon accounting. Examples include Pachama (<https://pachama.com/>), Upstream Tech (<https://www.upstream.tech/>), and NCX (<https://ncx.com/>), but except for Upstream Tech which relies on COMET-farm, the SOC is not accounted for. Compared to cropland systems, dMRV in forests remains more focused on land cover change and aboveground biomass estimation. To fully integrate SOC, forest dMRV systems should enable ingestion of site-specific SOC observations and model outputs, track litter and root inputs using remote sensing proxies (e.g., LAI), and apply spatial stratification strategies to reduce uncertainty. These features are essential for building credibility in carbon markets and aligning dMRV platforms with Tier 3 IPCC methodologies.

3.2.6 Recommendation on method selection based on context and data

Selecting suitable MRV methods for forest SOC should be context-specific, guided by the type and intensity of forest management, ecosystem characteristics, available data, and project-specific goals. In actively managed plantations or agroforestry systems, MRV methods should prioritize high temporal resolution and frequent biomass turnover monitoring, leveraging remote sensing technologies for rapid data acquisition. Conversely, unmanaged or naturally regenerating forests require MRV approaches focused on capturing slow-turnover carbon processes, legacy effects of historical disturbances, and natural regeneration patterns. Such forests often necessitate longer intervals between monitoring cycles and deeper historical land-use reconstructions. Selecting modeling methods that explicitly represent slow carbon turnover, litter dynamics, and root processes is recommended for such contexts. Lastly, the choice of IPCC Tier level (Tier 1, Tier 2, or Tier 3) should align with project scale, objectives, data availability, and required accuracy. While Tier 1 or Tier 2 methods might suffice for broad-scale national inventories or preliminary assessments, Tier 3 methods, incorporating detailed, site-specific measurements and advanced modeling, are strongly recommended for project-level reporting or crediting schemes where accuracy and reliability are critical.

4 Multi-ecosystems MRV

Different land covers or land uses are associated to different levels of SOC contents. Accordingly, land-use change to and from cropland, pastureland, forests and other types of land are associated with changes in SOC. In general, cropland SOC content is lower than SOC in other types of land (Beillouin et al. 2023). The change in SOC happens dynamically over time and may take a long time to reach a new state after land use change (Poeplau et al. 2011).

The preservation and restoration of SOC alone represent up to 25% of the potential of all nature-based solutions (NBS) to combat climate change (Bossio et al., 2020). Recent research has highlighted that the impact of land-use-change on soil organic carbon (SOC) is considerably greater than that of direct climatic factors. Beillouin et al. (2023) estimate that the effect of land conversion on SOC is seven to ten times stronger per unit area than that of climate drivers such as temperature rise or elevated atmospheric CO₂ concentrations. Converting forests, grasslands, or wetlands into croplands typically results in average SOC losses of approximately 25%, 16%, and 25%, respectively. Given that nearly one million square kilometres have been converted to cropland in the past six decades, these transformations have significantly contributed to rising atmospheric CO₂ levels.

Such land-use changes entail long-lasting consequences: once depleted, SOC stocks require decades—or longer—to recover, even under restorative management practices (Dignac et al., 2017). For instance, in French Guiana, Stahl et al. (2017) demonstrated that SOC stocks in grasslands established after deforestation (without burning) can return to pre-deforestation levels within 24 years when managed through rotational grazing and legumes. Furthermore, SOC continued to accumulate at depth (>1 m), with sequestration rates reaching up to $1.27 \pm 0.37 \text{ tC ha}^{-1} \text{ yr}^{-1}$ (Stahl et al., 2016; Blanfort et al., 2022). However, it is important to note that carbon losses from forest biomass due to deforestation are permanent unless agricultural use is stopped, in which case forest often regrow naturally. Secondary forests may be different from primary forests, therefore part of the changes of carbon sequestration in biomass are irreversible at human timescales. Despite this, systematic studies assessing the impact of land-use change on SOC remain scarce, particularly in regions such as North Africa, Central Africa, the Middle East, and Central Asia. It is equally important to acknowledge the inherent fragility of soil carbon (SOC) stocks. Sequestration gains can be rapidly reversed through land-use change, inappropriate grazing management, soil disturbance, fertilisation practices, or rising temperatures (Edouard-Rambaut et al., 2022).

Conversion of forests or grasslands into croplands usually results in significant SOC losses, and although conservation practices such as crop rotation, reduced tillage, and residue incorporation can partially restore SOC, these gains are often fragile and highly dependent on continuous management and external inputs. By contrast, pastures—especially permanent or well-managed grasslands—tend to maintain larger and more stable SOC stocks, often extending to deeper horizons (up to 1 m). This stability arises from continuous root inputs, litter deposition, and organic matter recycling through grazing animals. Furthermore, the diversity of plant functional types (C3 and C4 grasses, legumes) and the return of manure to the soil promote SOC stabilization and sequestration. However, pastures are

not free from risks: overgrazing, erosion, fire, and degradation can rapidly erode their carbon storage potential, particularly in tropical and semi-arid zones.

It is therefore interesting to consider land use change in SOC MRV schemes for different purposes. First, MRV scheme may propose land use change as a way to get credits for SOC increase (FAO, 2020a). Modelling or observing SOC change following land use change may also be helpful in the determination of initial SOC stocks in soils and baseline SOC dynamics related to previous land use change rather than to an intervention. The overall design of MRV framework may also need to be modified when the possibility of land use change is considered. Considering changes in practices for an unchanged land use, as already analysed in the previous part of this deliverable and other deliverables of the Orcasa project may require revaluation when the possibility of land use change is acknowledged.

The issue of reversibility, or lack of permanence of SOC change in soil may already be a difficult issue for changes in agricultural practices. Changing land use after a period of SOC monitoring could produce, in some cases, changes in SOC much more important than stopping to use a practice and question the permanence of SOC in soils. Some MRV schemes distinguish a crediting period and a permanence checking period to avoid issues related to non-permanence, with a permanence checking period that may be relatively long, up to 100 years (SoilEnrichment protocol, 2020). For the permanence checking period, it may be relevant to have some data on SOC change that could occur with land use change happening during that period.

4.1 An integrated MRV framework for the different land-uses

Taking into account land use change and change in SOC is relevant when such changes have occurred in the past and may occur in the future in landscapes with various possible land uses. For example, livestock systems in tropical regions operate across multiple ecosystems—ranging from humid savannas and drylands to frontier landscapes. livestock plays an ambivalent role: it has historically driven deforestation and land degradation but also provides opportunities for ecosystem restoration and climate mitigation when managed under sustainable frameworks. This complexity underscores the need for multi-ecosystem MRV approaches that capture both the risks and potentials of grazing systems across diverse landscapes.

In case of mandatory accounting schemes, land-use change needs to be accounted for. MRV schemes may have eligibility criteria that exclude from the scheme lands having experienced changes that lead to SOC decrease recently (FAO 2020a), as a way to penalize land use change that leads to SOC decrease, removing the need to evaluate precisely the SOC change for such transitions. In this case, the effect of past land use change may still be present if the dynamics of SOC change following land use change is longer than the time span corresponding to the cut-off date.

In addition to determining credits for SOC change following land use change as an intervention, including land use change in MRV scheme also allows to keep on monitoring SOC change after an unexpected land use change in an active monitoring period or in a permanence checking period.

4.2 Change of a land cover/land use to another on SOC

Land-use change (LUC), such as deforestation, afforestation, reforestation, conversion between forest and agricultural land or between grassland and cropland, is a significant factor affecting SOC stocks. Accurate accounting for SOC changes linked to LUC is critical for reliable MRV, particularly within frameworks such as REDD+, compliance markets, and voluntary carbon standards like Verra's VCS or Gold Standard. When forests are cleared or converted to agriculture, substantial SOC losses typically occur due to increased decomposition rates driven by soil disturbance and changes in vegetation cover. Conversely, converting agricultural lands to forests (afforestation/reforestation) often results in SOC sequestration, although these gains occur slowly over decades as forest vegetation matures, and depends on the inherited SOC level.

The IPCC provides clear guidance on SOC accounting related to LUC through the land-use categories defined in the Good Practice Guidance for Land Use, Land-Use Change and Forestry (GPG - LULUCF), recommending a 20-year transition period during which lands remain classified under a transitional category (IPCC 2006, 2019). SOC monitoring under LULUCF typically involves comparing SOC stocks under the original and new land-use scenarios, using either default factors (Tier 1), regional or national specific data (Tier 2), or site-specific monitoring and modeling (Tier 3). For example, when agricultural land is afforested, IPCC recommends initial use of default SOC stock change factors if no better data are available. For Tier 2 or Tier 3, specific measurements of baseline SOC stocks before planting and periodic resampling after afforestation provide the most robust accounting.

Carbon standards such as Verra's VM0007 methodology for afforestation/reforestation projects explicitly account for SOC by comparing baseline SOC stocks (e.g., agriculture or degraded land) with SOC sequestration under the new forest. VM0007 allows the use of Tier 2 (regionally calibrated factors) or Tier 3 (direct measurement and modeling). Methodologies typically require a conservative approach, applying deductions or uncertainty discounts if data quality is insufficient (Verra, 2020). Conversely, for deforestation, SOC stock losses are usually estimated using Tier 1 or Tier 2 approaches due to difficulty in direct measurement post-deforestation. Historical satellite data (e.g., Landsat, Sentinel-2) and regional soil carbon databases (e.g., SoilGrids, FAO GSOC) can inform these estimations, improving baseline reliability.

Accurate SOC accounting during land-use changes requires integrating remote sensing, field sampling, historical data, and SOC modeling. Remote sensing provides spatially explicit and temporally consistent documentation of land-cover transitions, essential for determining the timing and extent of changes. Field campaigns for SOC sampling should ideally occur immediately before and periodically after land-use transitions, with depth-structured sampling reflecting IPCC guidelines (e.g., 0–30 cm minimum, ideally up to 1 meter). Historical land-cover datasets such as Global Forest Watch (GFW), European Space Agency (ESA) CCI Land Cover, and JRC land-use datasets are valuable for establishing historical baselines and reconstructing timelines of LUC events. National forest inventories and agricultural censuses provide complementary ground data for improved model calibration and validation.

Models such as CBM-CFS3, RothC, and CENTURY have modules or methods to explicitly simulate SOC responses to LUC. Process-based modeling provides better representation of legacy effects, gradual changes, and recovery trajectories after afforestation or disturbance. Model initialization requires

careful historical reconstruction of management, disturbance regimes, and land cover to capture long-term SOC dynamics effectively. Advanced modeling frameworks increasingly incorporate remote sensing-derived inputs (e.g., vegetation productivity indices), improving representation of vegetation dynamics following LUC, especially in tropical and subtropical regions. These integrations facilitate more accurate estimation of SOC changes by better reflecting shifts in vegetation inputs and decomposition conditions.

4.3 Recommendations for MRV

In contexts where changes in SOC are used to give credits, such as VCM, a platform financing the changes of practices may have mandatory rules to determine land-use change or previous land-use, or it could be voluntary, i.e. a farmer shows changes to have credits. In case of land-use change the different systems may lead to different results. How the previous land uses are taken into account and cut-off dates used to determine which land use is considered to be the previous land use may lead to very different SOC change evaluations. If the precedent land use is not taken into account or cut-off dates are not far enough in the past, there could be an incentive to replace land uses such as forests and grasslands with land use with less carbon and then get subsidies to increase carbon. Since natural vegetation replaces cropland and grasslands when left unused, returning to the natural vegetation status should always be possible, and potential vegetation and SOC could always be used as a proxy for a cut-off date representing natural vegetation status (Searchinger et al. 2018). If not taken into account in MRV schemes, a short view on the preceding land use may favour land where SOC was depleted in the past, somewhat similar to the "hot air" issue for GHG emissions targets, that favour inefficient emitters per capita or per unit of product with high emissions levels that can relatively easily decrease some emissions.

In a longer-term perspective, taking the previous argument to the limit, there could be an incentive to intentionally deplete SOC through land-use change and get recurring credits for the increase of SOC back to past levels if the cut-off dates are not far away enough in the past or permanence and non-reversibility constraints are not strict enough and SOC monitoring is not mandatory over long times. The same incentive exists for changes in agricultural practices, but the consequences would be much more important with land use change.

Taking into account possible land-use change also gives space for crediting unchanged land uses SOC protection, as is done for example in the REDD+ framework. Indeed, keeping grasslands and forests instead of converting to cropland avoids decreasing SOC and may require re-thinking interventions as including doing nothing against a counterfactual where land-use change would happen, in particular if economically profitable because of high prices and existing or increasing demand for agricultural products.

Keeping SOC or allowing natural vegetation to regrow to increase SOC contents is relevant when considering the local SOC changes consequences only. However, these interventions also maximize the leakages and indirect land-use changes, described in more details in section 6.2.4. Indeed, if yields and demands do not change, abandoning agriculture means that some natural vegetation replacement will occur elsewhere. Similarly, replacing natural vegetation could be relevant if the overall balance in SOC

change is better than in other places where agricultural expansions or abandonment would otherwise happen. Therefore, the protection of SOC stocks should be considered together with leakages associated to production change.

5 Recommendations on transfers and leakages

A leakage happens when, as a consequence of an intervention that increases SOC carbon, SOC carbon decreases elsewhere. The purpose of SOC change evaluation is, in the vast majority of cases, associated to GHG reduction emissions. Therefore, a leakage, is also understood in a broader sense in the following if, as a consequence of an intervention that increases SOC carbon, net GHG emissions increase. Concentrating on local SOC changes only therefore bears the risk of increasing SOC to the detriment of other carbon pools, including SOC elsewhere and increasing GHG emissions. If an MRV scheme does not prevent all kind of leakages and is subsidized, in addition to environmental inefficiency, there is economic inefficiency and a risk to undermine confidence in such frameworks. Practice based interventions are simple, and it could be made sure that their direct effect on SOC is positive, however such interventions are particularly prone to leakages and transfers if strong ineligibility criteria ensuring that there is no leakage are not associated to the changes in practices.

Analysis of leakages related to SOC change are sparse in the literature, however, leakages described for other similar GHG reductions options can be mobilized. Biofuel development policies for GHG emissions reductions, in particular, lead to several publications on external input uses, land-use change and indirect effects (Fargione et al., 2008; Searchinger et al., 2008).

5.1 Transfers and leakages in existing MRV frameworks

In MRV schemes, requiring net GHG emissions decrease is often considered (CRCF, FAO 2020a). Transfers from other pools as organic amendments may also be considered as an ineligibility criterion (SoilEnrichment protocol, 2020). Leakage may also happen through trade. In general, demand change is better considered outside of the scope of the intervention, therefore reductions in productions need to be compensated for by production elsewhere, with associated SOC decrease and GHG emissions increases. This leakage is considered in SoilEnrichment protocol, 2020, with a comparison with long-term actual production change regional averages to be compared with the intervention change in production. If the intervention leads to a decrease in production compared to the trend above a 5% threshold, there is a proportional reduction of credits.

5.2 Leakages and their assessments

In the following, diverse leakages are detailed, with possibilities to account for the effects on SOC or GHG emissions. If a simple handling of leakages is desirable, the accounting can be cast in equivalent

no-leakage eligibility criteria, such as no decrease in production compared to the baseline, no increase in input use, no outside residues or grass use change. The use of such criteria will, however, prevent any trade-offs between the intensity of leakages and the magnitude of the direct intervention effect.

5.2.1 Transfers of external carbon to soil

The SOC increase should not come from carbon that depletes a carbon stock or carbon that could have been stored elsewhere, in biomass or soil. This is all the more important that the magnitude of this effect could surpass the carbon stored in SOC. In practice, this means that SOC carbon should come from the intervention area from photosynthesis, be it through roots, residues or grass, possibly after ingestion and excretion by livestock. External carbon imports should be accounted for as negative credits, except for grains that are also necessarily coming from photosynthesis and are, in general, not considered as stored carbon. If residues or grass comes from other locations, however, this means less carbon stored in other locations soils and possible decrease in SOC there. Similarly, if biomass stored in perennial vegetation, such as trees is used to increase SOC carbon, it should be accounted for as a loss.

Lateral transfers from places outside of the intervention area, and transfers from soil deeper than the monitored soil depth should not be accounted for as increase in SOC unless they are already accounted for as a loss where they come from. For example, if erosion brings SOC to an intervention area, this SOC change should not be credited. For carbon migrating from deeper soil, monitoring deeper than the specified depth could be a possibility to account for and remove this SOC change (SoilEnrichment protocol, 2020).

5.2.2 Change in direct GHG emissions associated to interventions

In general, increased yields lead to increased residues and to increased SOC in soils. However, if more fertilizer is used, increase in N₂O emissions will penalize the net GHG reduction effect of the increased SOC. To account for leakages in a broad sense through GHG emissions, GHG accounting tools can be used to determine the effect of the intervention on net emissions changes compared to the baseline, such that credits are lost if net emissions increase. The scope of the tools used should be as broad as possible to really avoid biased evaluations. A vast number of GHG calculators at the farm scale and beyond exist, with, among others, diverse level of accounting for SOC (Casson et al. 2023). For example, building on the knowledge acquired on SOC in tropical long-term pastures, the ACCT-DOM Guyane tool was developed as a localized adaptation of the European AgriClimateChange Tools (ACCTools). This instrument estimates the annual energy balance and GHG emissions at the farm scale, while also accounting for carbon storage in soils and biomass. Such life-cycle-based methodologies have since been applied beyond French Guiana, notably in Brazil (ACCT-PARÁ; Da Cruz Corrêa et al., 2025) and New Caledonia, underscoring their versatility in supporting MRV systems for sustainable livestock transitions (see section 2.1.2.5).

Livestock systems, due to their specificity and heterogeneity remain challenging to represent in GHG emissions accounting tools, especially for tropical livestock. A regional analysis by Gerber et al. (2013)

shows that greenhouse gas (GHG) emission intensities are highest in sub-Saharan Africa—mainly due to large herd sizes coupled with low productivity—and in Latin America and the Caribbean, where deforestation from the conversion of primary forests into pasture and feed crops is the primary driver. These systems can reach greenhouse gas (GHG) emission intensities of approximately 70 kg CO₂-eq per kilogram of carcass produced, a value that is considerably higher than in many temperate production systems. Such figures, however, should be interpreted with caution. They reflect broad regional averages and mask substantial heterogeneity across livestock systems in low- and middle-income countries (LMICs). For instance, pastoral and agropastoral systems, mixed crop–livestock systems, and intensive feed-based operations differ greatly in terms of productivity, input use, land management, and associated GHG emissions. The reliance on aggregate statistics often obscures these contrasts, giving the misleading impression of uniformly high emission intensities. In reality, the performance of livestock systems is shaped by a wide array of factors—including breed type, feeding regimes, manure management, grazing pressure, and land-use change dynamics—that vary markedly across regions and production systems.

Only through disaggregated, system-level analyses can this complexity be properly captured. Recent efforts by research have begun to provide more nuanced insights, revealing that some extensive systems approach carbon neutrality when soil carbon sequestration and ecosystem services are accounted for. Such differentiated assessments are critical for designing effective mitigation strategies, informing MRV frameworks, and ensuring that NDCs reflect the diversity of livestock systems in LMICs rather than relying on oversimplified averages (Assouma, 2016; Assouma et al., 2019; Blanfort et al., 2022).

Livestock farming in the Sahel is frequently cited among the production systems with the highest GHG emission intensities, when assessed on a per-unit-of-product basis (meat, milk, etc.). Such metrics tend to disadvantage extensive pastoral and agropastoral systems, which are inherently characterized by low productivity. However, ecosystem-based assessments that account for both livestock-related emissions and carbon sequestration in pastoral ecosystems demonstrate that Sahelian pastoral systems can potentially follow a trajectory approaching carbon neutrality. These systems show a measurable though modest sequestration potential of $40 \pm 6 \text{ kg C ha}^{-1} \text{ yr}^{-1}$). This body of research is embedded within the CASSECS project (Supporting Innovation for the Resilience of Pastoral and Agropastoral Livestock Systems in Sahelian CILSS Countries; www.cassecs.org).

5.2.3 Change in input requirement

If an intervention requires a change in input from outside of the intervention area compared to the baseline, the consequences on their production for SOC change and net GHG emissions should be accounted for, in the spirit of life cycle assessment (LCA). For example, if the intervention requires more grain, associated SOC removal from land-use change and production and land-use change emissions should be accounted for. GHG calculators can be used for that purpose, however it is important to note that indirect land-use change, and associated SOC or GHG emissions is not often evaluated in those tools, which could bias considerably the evaluation (Searchinger et al. 2018).

Since the input used are produced elsewhere, the validation of the coefficients used in assessing the changes in SOC or GHG is more difficult to achieve, as the whole MRV framework cannot, in general,

be extended to the external input's providers. There is also a risk of double counting, if the input production is already subject to an MRV system or other type of accounting.

5.2.4 Change in production levels

In general, demand change is outside of the scope of the intervention, therefore changes in production compared to the baseline should lead to increased or decreased credits corresponding to the production differential. This corresponds conceptually to the accounting of carbon benefits of agricultural production (Searchinger et al. 2018). This is important for changes in production levels, when the land use do not change, but also for change in product and change in land use. This is particularly important, because the magnitude of displacement of production could easily overcome the quantity of locally stored carbon in SOC, since the amplitude of this effect can potentially be important, as it is not directly related to the local change in SOC.

Different options exist for this accounting. A simple possibility is to proportionally modify the credits, assuming that production systems are in similar situations as the intervention system (SoilEnrichment protocol, 2020). In consequential LCA, the marginal provider of substituted input or output is considered and the analysis is extended to include the SOC or emissions added or removed. The choice of the marginal provider can lead to different results requiring hypotheses or uncertainty analyses (Styles et al. 2018). Another option is to consider that through local or global markets replacement concerns all the producers based on their share in production, using average emissions coefficients (Searchinger et al. 2018). The choice of the specific method could depend on the likelihood of replacement sources, and also on the simplicity of the method, in which case conservative assumptions should be used to limit the risk of having a reversal in the sign of the overall effect.

A difficulty related to the long times required by SOC interventions and permanence checking is that the factors that should be used for the evaluation of production change consequences on SOC and GHG emissions should be projected although they depend on the uncertain future evolution of technology and agriculture GHG emissions and SOC change mitigation policies.

Note that, by this reasoning, an intervention that leads to a local decrease in SOC more than compensated by an overall decrease in SOC through an increase of production compared to the baseline could possibly be eligible to credits, in line with a carbon opportunity cost reasoning applied to SOC. More generally considering that production avoids carbon losses and emissions elsewhere changes the focus from avoided deforestation to targeting of agricultural production location where production is high relatively to removed carbon and production emissions.

As highlighted by Pocard-Chapuis et al. (2021, 2024), in frontier regions like the Amazon, rangeland expansion has contributed massively to deforestation, releasing carbon from forest biomass and degrading soils. Amazonian livestock is therefore facing global criticism. Yet, innovative management practices—such as dynamic rotational grazing—can restore soil fertility, stimulate belowground biomass production, and lead to significant soil organic carbon (SOC) sequestration (Pocard-Chapuis et al., 2021). In line with carbon benefits reasoning, it is possible to have both locations where intensification occurs to satisfy the demand, where carbon in SOC or in biomass would be as limited as possible compared to the production, and other places that should be not be used for agriculture, such

that secondary forest regrowth can happen, both for carbon sequestration and biodiversity preservation.

However, MRV frameworks for these systems must extend beyond single-farm or single-ecosystem scales, integrating spatial heterogeneity and governance dimensions. For instance, territorial certification and jurisdictional approaches (Brandão et al., 2020) demonstrate how MRV can embed livestock performance into broader land-use planning, aligning with NDCs and low-carbon development trajectories. In that context, degraded pastures abandoned under improved systems contribute to secondary forest regrowth, adding another ecosystem dimension to carbon accounting.

To address this, the concept of territorial certification has emerged (Poccard-Chapuis et al., 2024). Unlike traditional farm or product certification, it evaluates territorial processes (land-use transitions, local institutional performance, landscape efficiency) without requiring costly product traceability. This avoids the bias of certifying only elite farms and enables systemic impacts across entire territories. Territorial certification is thus oriented towards investors and policy incentives rather than consumer markets, which are less relevant in the Amazon's commodity-based economy. Its purpose is to demonstrate territorial progress, differentiate regions according to their governance and sustainability trajectories, and encourage responsible development pathways, beyond simply controlling deforestation.

Primary forests being in general more interesting than secondary forests for carbon storage in biomass and soil, and for biodiversity conservation, eligibility criteria that avoid direct deforestation remain important, and avoiding deforestation is an important goal in itself. On already deforested areas, targeting both rewilding and sustainable agricultural intensification could be relevant for carbon storage and GHG emissions reductions. In that case, eligibility criteria become even more important to avoid pollution displacement, as intensification comes with other environmental consequences, such as nitrogen pollution and pesticides pollution.

5.2.5 Other possible leakages

Other leakages are possible, for instance through price effects. For example, if an intervention leads to a decrease in the relative price of a product with high SOC or GHG intensity, leading to an increase of the associated demand. More generally, changes of input, labour or production have economy-wide consequences through general equilibrium and trade effects that feedback on SOC and GHG emissions changes.

If the analysis is extended to consequences to climate instead of GHG emissions, changes in other parameters such as albedo, vegetation roughness or water use affect the climate with effects on the local (Pielker et al. 2007) or global climate (Guimberteau et al. 2011). Changes in practice or land use have other distant effects on the water and nitrogen cycle, on pesticides and nitrogen pollution, with possible feedback on SOC and GHG emissions changes.

It is not possible to account for all the indirect effects and leakages, however in MRV frameworks design, it should be accounted for that some feedback and indirect changes are missed and some provision for the risk of interventions having unintended consequences should be considered.

5.3 Baselines for leakage assessment

As shown above, accounting for leakages requires additional information for the counterfactual no-intervention baseline. In particular, all the variables that are relevant for GHG emissions assessments, including changes in input use and in input SOC and GHG footprints, but also on trends of production changes.

5.4 Consequences of MRV framework design and implementation

The design choices of MRV frameworks, accounting protocols and inventories have, by themselves, consequences that may feed back on SOC and GHG emissions changes. Indeed, technical choices, but also choices in term of governance or financing foster visions of the economy and society, institutional change, requires input, and favour economical agents, in particular farmers and businesses in certification, measuring and finance. In turn, through social networks, economic global equilibrium and trade or through input production and substitutions effects, distribution of wealth, demand patterns, activity and production change, and ultimately feed back on SOC and GHG emissions change. The distributional effects of subsidized MRV framework could particularly be important. Even though these effects may be difficult to predict precisely and are often over-determined by political choices, it should be accounted for that some feedback and indirect changes are necessarily associated to the setup of MRV and accounting systems and some provision for the risk of interventions having unintended consequences should be considered.

6 Discussion and perspectives

Nationally Determined Contributions (NDCs) are the main framework through which countries commit to climate action. Agriculture, and particularly livestock, plays a central role, yet its monitoring remains partial. Soil Organic Carbon (SOC) is widely recognized as a major lever for both emission reductions and carbon sequestration, but it is still underrepresented in NDCs: only about ten countries explicitly mention SOC, while more than forty include relevant practices without setting quantitative targets. Building a low cost, simple and robust integrative MRV framework for SOC stock changes is essential to make agriculture related NDCs measurable, reportable, and verifiable. It strengthens the scientific credibility of commitments, unlocks access to climate finance, and highlights agriculture not only as emitter but also as agents of carbon sequestration and ecosystem resilience (Rose et al. 2020, 2021).

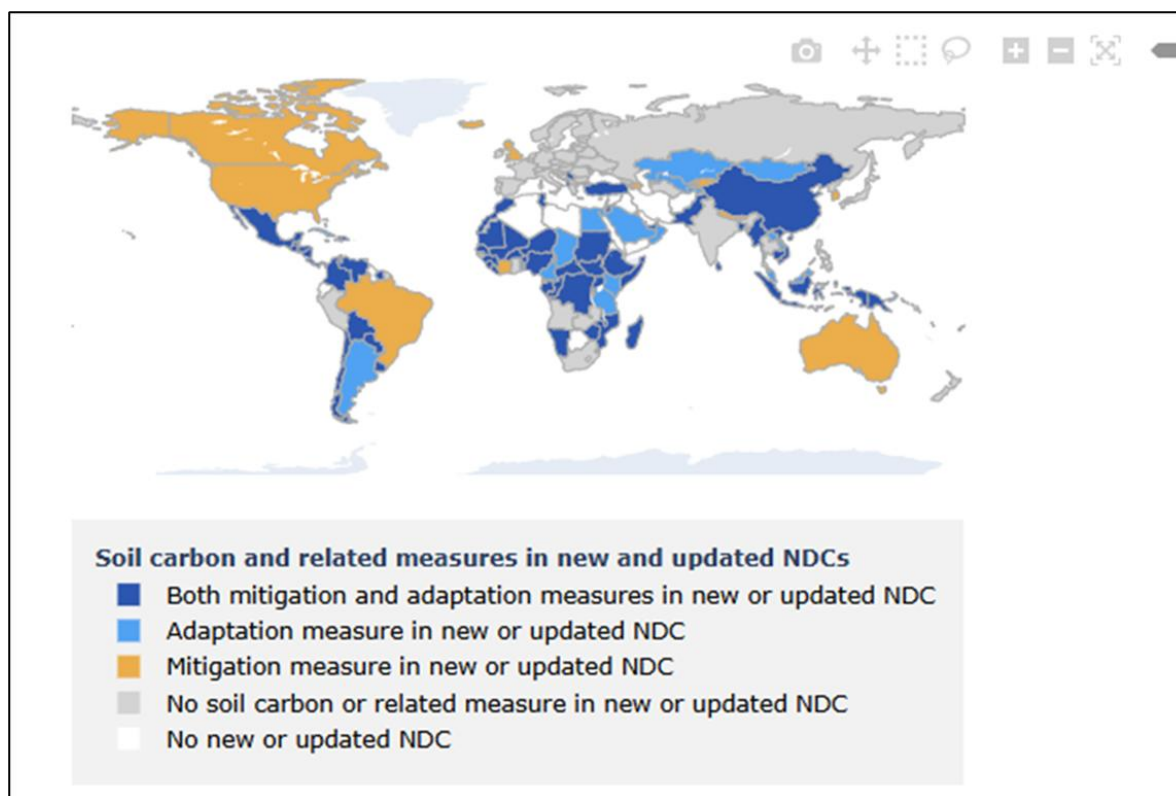


Figure 2: Map of countries of Soil carbon and related measures in new and updated NDCs (Rose and al., 2021)

The review of the literature and existing MRV frameworks shows that the type of tools that can be used for monitoring of SOC change in grassland, rangelands and forests are similar to those for croplands, with suitable adaptations. The case of transhumant systems and communal grasslands, however, requires rethinking MRV to add the possibility to monitor changes systems at the landscape level, even for voluntary carbon credit markets, which could target livestock herders. More generally, differences between production oriented large and homogeneous systems mainly found in temperate climates and other systems are important for forests and even more for rangelands, and would require important adaptation of SOC MRV, with local participatory systems being a possible option.

Forest and grassland and pastureland building blocks usable for SOC MRV are less developed outside of research than similar tools for croplands, however the on-going developments give insurance that integrated processing chains based on measurements in specific plots, modelling and earth observation and DTS adapted to forests and grassland will be ready in the years to come for Tier2/3 level monitoring, together with associated data infrastructures.

However, challenges for MRV systems for grasslands and forests, even with more accurate and cheaper processing chains remain. Indeed, monitoring SOC in forest ecosystems differs markedly from cropland due to slower dynamics, deeper carbon pools, and limited direct management interventions. Grassland and rangelands are intermediary in term of dynamics, and are also characterized by deeper carbon pools. Carbon stored in grasslands and forests is in general more stable than in croplands, but bears

more risks of losing large quantities of accumulated carbon because of land use change or disturbances. Long times, diverse practices, risks of non-permanence remain challenging for the implementation of MRV systems, independently of the accuracy of the monitoring.

The consequences of land use change, especially relevant for forest and grassland that store more carbon in SOC than croplands, the use of MRV for NDC and the possibility to use similar frameworks for the different land uses call for multi-ecosystem MRV which should:

- Monitor SOC changes across interconnected units (pastures, forests, croplands, wetlands) within a landscape;
- Account for the dual impacts of livestock and cultivation—both degradation and restoration—under different management regimes;
- Prioritize conservation of carbon rich primary or mature systems;
- Provide with multi-scale monitoring, for farms, but also landscapes;
- Integrate socio-economic drivers such as land tenure, mobility, and territorial governance, which strongly influence land-use change dynamics;

The lack of harmonized indicators and methodologies tailored to diverse ecosystems (in particular tropical systems) still undermines the credibility of national inventories. MRV frameworks therefore emerge as an indispensable tool to bridge this gap. They must combine direct measurements, modeling, Earth Observation, and participatory monitoring to adequately reflect the diversity of contexts. By improving transparency, comparability, and accuracy, an integrated multi-ecosystem SOC MRV framework would strengthen countries' ability to justify their mitigation targets, secure climate finance, and increase the ambition of their NDCs. It would also reconcile mitigation and adaptation, acknowledging the multiple environmental and socio-economic functions of agriculture and livestock within landscapes (notably food security, biodiversity). In this sense, developing MRV systems for SOC stock changes constitutes a strategic lever to link global climate policy with local dynamics, while consolidating the contribution of sustainable agricultural systems to NDC implementation.

In addition to permanence, accuracy and additionality, it is crucial to take into account leakages and transfers in the design of MRV systems, as the magnitude of the effects can be similar to the locally accumulated carbon in SOC, potentially leading to a reversal of the overall effect of the intervention. Accounting for displacement of production tend to favour higher yielding systems in relation to the SOC carbon they can accumulate, but bears the risk of increased pollution, therefore provision for other environmental impacts than GHG emissions reductions and SOC increase should be incorporated in MRV frameworks to avoid pollution displacement. Research linking MRV systems design and leakages assessment should also be more important, such that this aspect, which is not as “marketable” as the development of new technologies for monitoring but important for the credibility of the SOC change MRV systems becomes an integral part of all the MRV systems for SOC change.

Abbreviations and acronyms

Acronym	Description
A/R	Afforestation/Reforestation
ACCT	AgriClimateChange Tools
AFOLU	Agriculture, Forestry and Other Land Uses
ANN	Artificial Neural Networks
API	Application Programming Interface
ART	Architecture for REDD+ Transactions
BAU	Business As Usual
C	Carbon
CAP	Common Agricultural Policy
CASSECS	Supporting Innovation for the Resilience of Pastoral and Agropastoral Livestock Systems in Sahelian CILSS Countries
CRCF	European Carbon Removal Certification Framework Regulation
CCAFS	Research program on Climate Change, Agriculture and Food Security
CSV	Comma Separated Value
CWD	Coarse Woody Debris
DNDC	DeNitrification-DeComposition
DL	Deep Learning
DSM	Digital Soil Mapping
DST	Decision Support Tool
EO	Earth Observation
ESA	European Space Agency
EU	European Union
EVI	Enhanced Vegetation Index
EX-ACT	Ex-Ante Carbon-balance Tool
FAO	Food and Agriculture Organization of the United Nations
FMIS	Farm Management Information System

Acronym	Description
FSC	Forest Stewardship Council
GFW	Global Forest Watch
GHG	Greenhouse Gas
GLEAM	Global Livestock Environmental Assessment Model
GLAI	Green Leaf Area Index
GPG-LULUCF	Good Practice Guidance for Land Use, Land-Use Change and Forestry
GRA	Global Research Alliance
GSOC	Global Soil Organic Carbon map
IEM	Integral Equation Model
IFM	Improved Forest Management
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
ITPS	Intergovernmental Technical Panel on Soils
JRC	Joint Research Centre
JREDD	Jurisdictional REDD
LAI	Leaf Area Index
LCA	Life Cycle Assessment
LiDAR	Light Detection And Ranging
LMIC	Low- and Middle-Income Countries
LUCAS	Land Use and Coverage Area frame Survey
LUH2	Global Land-Use Harmonization dataset
LULUCF	Land-Use, Land Use Change and Forestry
MIR	Mid Infrared
ML	Machine Learning
MLR	Multi Linear Regressions
MODIS	Moderate Resolution Imaging Spectroradiometer
MRV	Monitoring, Reporting and Verification

Acronym	Description
NBS	Nature-Based Solutions
NDC	Nationally Determined Contribution
NDVI	Normalized Difference Vegetation Index
NGO	Non-Governmental Organization
NIR	Near Infrared
NPP	Net Primary Productivity
PEFC	Programme for the Endorsement of Forest Certification
PRODES	Projeto de Monitoramento do Desmatamento na Amazônia Legal por Satélite
PU	Public
RCTM	Rangeland Carbon Tracking and Management
REDD+	Reducing Emissions from Deforestation and forest Degradation, plus conservation, sustainable management and enhancement of carbon stocks
RF	Random Forest
RTM	Radiative Transfer Model
SAMPLES	Standard Assessment of Agricultural Mitigation Potential and Livelihoods
SAR	Synthetic Aperture Radar
SEPAL	System for Earth Observation Data Access, Processing and Analysis for Land Monitoring
SOC	Soil Organic Carbon
SVM	Support Vector Machine
TCCA	Transparency Comparability Consistency Completeness Accuracy
TMF	Tropical Moist Forest dataset
UAV	Unmanned Aerial Vehicle
UNFCCC	United Nations Framework Convention on Climate Change
VCM	Voluntary Carbon Market
VCS	Verified Carbon Standard
VOD	Vegetation Optical Depth
VWC	Volumetric Water Content
WCM	Water Cloud Model

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