SEQANA

Unpacking Equivalent Soil Mass (ESM):

Increasing precision and reducing costs for soil carbon MRV

Soil represents one of the largest active carbon reservoirs on Earth, and its accurate measurement underpins the credibility of any land-based carbon project. Despite this, the most widely used method for quantifying soil organic carbon (SOC) stocks, the Fixed Depth method, contains a fundamental methodological limitation that has direct consequences for the integrity of carbon credit accounting. Addressing this limitation is not merely a scientific refinement; it is a prerequisite for reducing risk by building carbon markets on defensible data.

The Equivalent Soil Mass (ESM) approach addresses this limitation and has been a requirement in the major soil carbon methodologies, including Verra's VM0042, for several years; however, it has often been overlooked or lacked clarity in how to best implement it on individual projects.

In this resource, we demystify ESM and explore the limitations of relying on Fixed Depth sampling methods. You will learn how ESM influences the quantification of your SOC stock changes, gain initial insights into establishing the reference soil mass, and discover the various methodologies available for implementing ESM within your project.

The problem with Fixed Depth (FD) sampling:

The conventional approach to SOC stock quantification is the Fixed Depth (FD) method: soil is sampled to a predetermined depth, typically 0–30 cm (IPCC, 2006), and SOC stocks are calculated by multiplying the measured carbon concentration (i.e. SOC%) by the sampled volume, corrected for bulk density. This approach is operationally straightforward and has dominated soil carbon science for decades.

Its central limitation, however, lies in what happens to soil physical structure under changing land management. Practices associated with soil health improvement like reduced tillage, cover cropping, organic matter additions tend to decrease soil compaction, increase porosity, and reduce bulk density (the dry mass of soil per unit volume). This structural change is a meaningful indicator of soil recovery. Yet it introduces a critical measurement artifact when fixed depths are used.

When bulk density decreases, the same volumetric column of soil, such as 0 to 30 cm, contains a smaller mass of mineral soil than it did at baseline. Comparing SOC stocks between two points in time using an identical depth interval therefore means comparing unequal quantities of soil mass.

Any observed change in carbon stock conflates genuine carbon gains or losses with shifts in the soil's physical structure. The FD method cannot distinguish between these two signals.

This is not a marginal source of error. Research has demonstrated that bulk density changes following management transitions can meaningfully bias SOC stock estimates (Lee et al. 2009) either underestimating sequestration where soils have become less dense, or producing apparent gains where none occurred. For carbon credit projects, where robust MRV is essential, this ambiguity in SOC stock estimates is untenable, especially since the bias potentially introduced by changes of BD can be higher than the changes of SOC stock itself.

What is Equivalent Soil Mass:

Equivalent Soil Mass (ESM) addresses this problem by replacing depth as the reference unit with mineral soil mass. Rather than comparing SOC stocks within identical depth intervals, ESM compares stocks within identical masses of mineral soil, anchored to a reference mass established at the initial sampling campaign.

The rationale is grounded in a straightforward principle: soil mineral matter (the sand, silt, and clay fraction) is functionally stable across management-driven changes. It does not accumulate or disappear at timescales relevant to carbon projects. Carbon, by contrast, is precisely what is being tracked. Normalizing SOC stock estimates to a fixed mineral mass therefore isolates the carbon, which is the variable of interest from the other confounding variables that drive changes in soil structure and density.

In practical terms, if a soil becomes less dense over time, an ESM-based calculation extends the sampling depth slightly beyond the initially sampled depth interval to incorporate enough additional soil to reach the reference mineral mass. The resulting SOC stock change estimate reflects carbon change alone, free from the distortion introduced by shifts in bulk density.

How ESM impacts SOC quantification tools in carbon projects:

The implications of ESM extend beyond individual measurements or projects. Across the principal frameworks and tools used in carbon accounting, ESM produces results with lower uncertainties, unlocking cost savings and increase in revenue for project developers.

Digital Soil Mapping

Digital Soil Mapping (DSM) generates spatial predictions of SOC stocks at scale, often forming a “ground-truth” reference against which project-level claims are assessed. When calibration data for DSMs are subject to FD-related biases, the resulting DSM inherits systematic errors that propagate through every downstream calculation.

Biogeochemical Models (BGCMs)

Biogeochemical Models (BGCMs) are used to model SOC stock changes and are calibrated against observed field data. FD-related biased calibration data produce biased model outputs. ESM-corrected datasets improve the accuracy of model parameterisation and, consequently, the reliability of model-based carbon estimations used to support credit issuance.

Sampling Design (SD)

When SOC stocks are estimated using FD methods, the SOC stock variance observed across a landscape reflects not only genuine spatial variability in SOC%, but also noise introduced by the spatial variability of bulk density. This inflated SOC stock variance increases the sample sizes required to achieve acceptable statistical confidence. ESM-corrected estimates remove bulk density as a confounding source of variance, producing a more accurate characterisation of true SOC stock spatial variability. As a result, the number of samples required to meet uncertainty thresholds may be reduced, with direct implications for the cost and revenue of large-scale carbon programmes.

Across all of these applications, the adoption of ESM strengthens the evidentiary basis of carbon stock estimates, reducing the risk of over- or under-crediting and improving the defensibility of reported outcomes under third-party verification.

Defining the reference Equivalent Soil Mass:

The selection of the reference equivalent soil mass (ESM) is a critical step in ensuring robust SOC stock comparisons. The reference mass should be defined based on the initial sampling event (t_0) and is typically chosen as either the minimum observed cumulative fine mineral soil mass or a lower percentile (e.g., the 10th percentile) across all sampling locations. This conservative choice ensures that all subsequent samples contain sufficient cumulative mass to allow interpolation of SOC stocks at the reference mass. By avoiding the need for extrapolation beyond the observed data range, this approach reduces uncertainty and improves the consistency and comparability of SOC stock estimates over time.

Methodologies for implementing ESM in SOC quantification:

Two broad methodological approaches exist for implementing ESM in SOC stock quantification. The first methodology, the ESM-based approach, expresses and compares carbon stocks per unit of mineral soil mass and replaces depth entirely as the reference unit. The second retains depth as the reporting unit but applies a correction derived from equivalent soil mass principles to account for bulk density change between sampling occasions. This is called the ESM-corrected approach. Both approaches are detailed below.

1: ESM-based approach

This approach is described in **Wendt & Hauser (2013)** and replaces depth entirely as the reference unit. Instead of reporting SOC stocks to a fixed depth, stocks are quantified relative to a defined mass of mineral soil. This ensures that comparisons across time are not affected by changes in soil compaction or structure, but it also shifts the reporting framework away from conventional depth-based units. Despite this, the Wendt & Hauser (2013) methodology is frequently cited because it establishes the conceptual and methodological foundation for how ESM is calculated and applied in sampling. A further limitation is that it does not separate fine earth from coarse fragments, treating the mineral soil mass as a single bulk quantity, which can bias carbon concentration, since organic matter is concentrated almost entirely in the fine fraction (Poeplau et al., 2017).

2: ESM-corrected approach

The second approach, known as the ESM-corrected approach, first computes SOC stocks using an equivalent fine mineral soil mass, following the same principle as the ESM-based approach, and then translates these results back into fixed depth intervals for reporting. This enables direct comparison with conventional depth-based datasets, while correcting for bias introduced through artifact-related changes in bulk density.

2a: Method proposed by Von Haden et. al. (2020)

The method proposed by **Von Haden et al. (2020)** is based on depth-resolved sampling, where multiple sub-depth intervals are collected and used to model the relationship between cumulative SOC and **fine mineral soil mass**, typically via interpolation (e.g., cubic spline or linear). This approach provides higher accuracy.

2b: Method proposed by Boivin et al. (2025)

Bolvin et al. (2025) propose a leaner alternative to full multi-layer sampling at every event: a single fixed-depth measurement at t_0 (e.g., 0–30 cm) serves directly as the reference mass, with one additional, deeper **correction layer** added only at resampling (t_n) to inform the interpolation back to that reference. **Potash et al. (2026)** provide the first empirical test of this design against a densely-sampled-at-depth reference dataset, finding it substantially reduces systematic error relative to uncorrected fixed-depth remeasurement — and that the correction layer can be pooled into a single composite sample per site without meaningfully degrading accuracy, as Boivin et al. also proposed.

2c: Method proposed by Fowler et al. (2023)

In contrast to the interpolation-based approaches above, the method proposed by **Fowler et al. (2023)** is designed for situations where only a single fixed-depth interval (e.g., 0–30 cm) is available. Rather than requiring multiple depth increments and interpolation, it solves for an **adjusted depth (Da)** by equating the fine mineral soil mass at t_0 and t_1 using bulk density and SOC concentration at both time points. SOC stocks are then calculated at Da, representing the depth at t_1 equivalent in soil mass to the original sampling depth at t_0. While more practical in contexts with historical fixed depth sampling, the method assumes homogeneity within the sampled layer and therefore introduces greater uncertainty compared to approaches based on sub-depth interval sampling[1]. As a result, when designing a sampling campaign from scratch, rather than starting with legacy fixed-depth data the authors note that interpolation approaches remain preferable.

Differences in sampling and analytical requirements from FD to ESM:

Transitioning to ESM-compatible sampling does not require a fundamental restructuring of field operations, but it does change what must be measured and how cores must be handled. The most significant practical shift is that **bulk density is no longer a required measurement**, it may still be recorded as a useful ancillary parameter, but it is not an input for ESM calculations. Instead, the critical requirement is that the soil is collected across **at least two contiguous depth increments**, each with its fine mass and SOC concentration recorded independently.

This can be achieved either by sectioning a single long core into discrete depth intervals after extraction, or by collecting multiple contiguous cylinders in sequence at the same location, each corresponding to a defined depth increment. In both cases, continuity between increments is essential. Gaps in the depth

[1] Fowler et al. also provide extensions for cases where more than one depth interval is available, applying the mass correction to the lowest sampled layer. However, the method remains algebraic rather than explicitly modelling the cumulative SOC-mass relationship across the profile, and as the authors themselves note, interpolation-based approaches remain preferable in terms of accuracy when data allow.

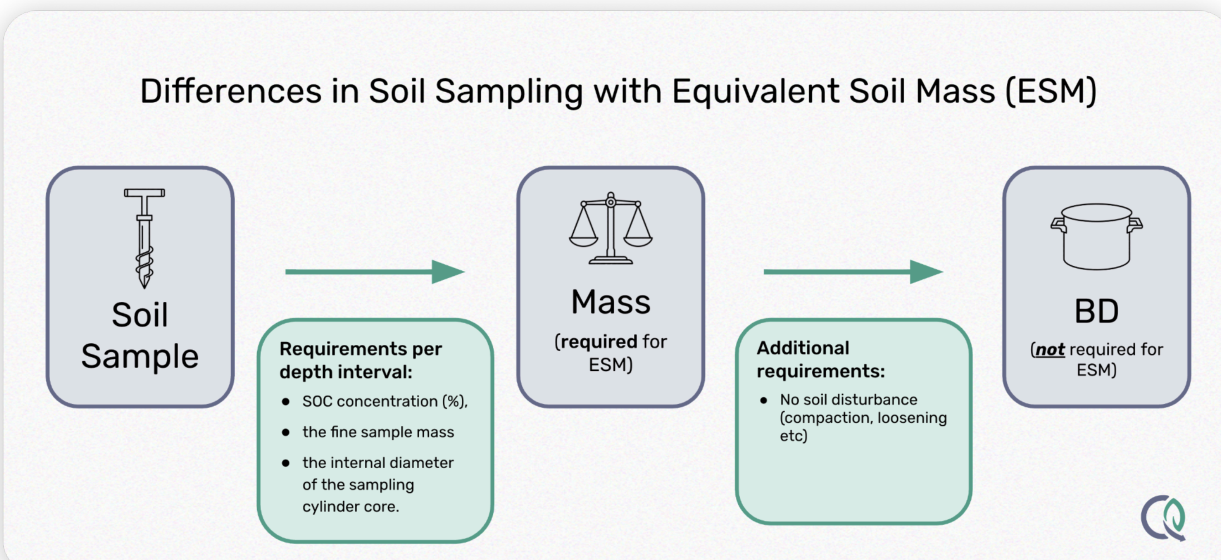
profile preclude the cumulative mass calculations on which ESM methods rely (Von Haden et al., 2020; Wendt & Hauser, 2013).

The parameters required per depth increment are:

- SOC concentration,
- the fine sample mass (the dry mass of the soil fraction below 2 mm after removal of coarse fragments),
- the internal diameter of the sampling core. *Note: From the core diameter, the cross-sectional sampling area is derived, allowing fine soil mineral mass to be expressed per unit area (typically Mg ha^{-1}).*

Fine soil mineral mass is then calculated by subtracting the estimated soil organic matter mass from the fine soil mass, isolating the mineral fraction that serves as the stable ESM reference.

Important Note: While the parameters listed above apply equally to BD, there is one critical difference. BD requires the soil structure and void space to remain entirely intact, meaning the soil *cannot* be disturbed (e.g. compacted or loosened). This restriction does *not* apply when sampling for soil mass. When sampling for mass, compaction does not corrupt your SOC stock calculations because carbon is contained in the mineral soil matrix rather than being tied to a fixed volume. This flexibility reduces measurement uncertainties, makes the sampling process easier and potentially more cost-effective.



Practical applications of ESM with Seqana:

The practical implementation of ESM requires more than just a careful understanding of the methodology. It requires clean data, the right measurements in the field and lab, and careful decisions at the outset of a project.

Seqana can support your project with best practices on data:

Data and Sampling Requirements:

If you are designing a new carbon program and building a Sampling Design with Seqana, we can advise on exactly what needs to be recorded, from the depth increments and core dimensions to the lab parameters required for accurate fine soil mineral mass determination. Our sampling designs ensure your approach aligns with relevant ISO norms for soil sampling and analysis.

Independent Validation of ESM calculations:

If you already have raw soil data, Seqana can run or independently verify your ESM-based SOC stock calculations, giving you and your stakeholders confidence in the numbers.

Establishing a baseline with ESM:

We can also help you think through one of the most consequential decisions in any ESM framework: how to establish the reference soil mass at project baseline.

Getting this right from the start avoids costly corrections down the line and ensures your monitoring data will hold up under third-party verification. Whether you are launching a new project or stress-testing an existing methodology, we are here to help you build on solid ground.

Conclusion

While the Fixed Depth (FD) method has long been the operational standard for SOC stock quantification due to its simplicity, its structural limitations are becoming increasingly difficult to justify. As the scientific and regulatory foundations of soil carbon markets mature, the potential for systematic misrepresentation introduced by FD has led most methodologies to mandate the Equivalent Soil Mass (ESM) method.

ESM provides a methodologically sound alternative by decoupling carbon stock estimates from the confounding effects of bulk density changes. Furthermore, approaches developed by researchers such as

Wendt & Hauser, Von Haden et al., Boivin et al., Potash et al., and Fowler et al. offer practical implementation pathways for projects at any stage of data collection or monitoring design.

For practitioners, project developers, and methodological bodies operating in voluntary or compliance carbon markets, adopting ESM-compatible frameworks is a critical step toward the measurement rigor that credible carbon accounting demands. Partnering with the right experts can help you seamlessly integrate ESM into your sampling design and workflows for digital soil mapping (DSM) and biogeochemical modeling (BGCM), ultimately unlocking lower uncertainty deductions and reducing sampling costs.

Seqana is equipped to support your project with industry-leading data practices.

Ready to see how Seqana can help you implement Equivalent Soil Mass for your project?

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