Independent Expert Report: estimating organic carbon stocks using digital soil mapping: Calibration, validation, and uncertainty estimation

Methodology Title	Estimating organic carbon stock using digital soil mapping: calibration, validation and uncertainty estimation (ID#CN0137)
Version	1.0
Sectoral Scope(s)	14. Agriculture, forestry and other land use (AFOLU)
Document Reviewed	Estimating organic carbon stock using digital soil mapping: calibration, validation and uncertainty estimation (ID#CN0137)
Date of Issue	August 14, 2025
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1 INTRODUCTION

Verra is managing the development of a new VCS Tool for quantifying organic carbon stocks using digital soil mapping: calibration, validation and uncertainty estimation (ID#CN0137). Per section 2.1.2 of the *Methodology Development and Review Process, v4.4*, this methodology is being developed through an alternative process that has been deemed more efficient and equally robust. The alternative process included:

1) Replacement of Section 3.5 Step 5: Validation/verification body assessment of methodology with review by a group of independent experts and a limited scope VVB assessment
2) Conducting the review of the revised draft after public consultation by a group of independent experts

Based on their experience in the use of digital soil mapping for quantification of soil organic carbon stock and project development for the carbon market, Perennial Climate Inc. hired the Independent Experts identified above to provide an expert assessment of the proposed methodology. These experts bring expertise in methodology development for voluntary carbon markets, including the development of existing VCS methodologies, modules and tools, expertise in digital soil mapping, remote sensing of carbon, and statistical procedures in carbon accounting.

The assessment of the Expert Assessors focused on:

1) Scientific rigor: Assessment of whether the methodology reflects the most recent scientific knowledge on the use of digital soil mapping for the quantification of soil organic carbon stock changes in agricultural land;
2) Technical robustness, consistency, accuracy and/or conservativeness of:
    a. The procedures for the application of DSM for quantification of soil carbon stock changes
    b. The guidance for the development and selection of models, including the selection of data and parameters
    c. The guidance for soil sampling for DSM calibration, validation and re-calibration, and uncertainty estimation
    d. The guidance for the development and selection of models, including selection of data and parameters
    e. The overall robustness and practical applicability of the tool
3) The completeness of the developer responses to public consultation feedback

2 Assessment Approach & Findings

The expert assessors reviewed the draft methodology that was revised following the public consultation and provided feedback to Verra. Perennial Climate Inc. prepared responses to the expert assessor's findings and updated the methodology accordingly. The expert assessors reviewed the responses and provided confirmation that the planned updates address the findings. This process proceeded through multiple rounds of feedback and methodology updates, including a 3-day in-person workshop in Boulder, Colorado, USA, over the course of 15 months. See section 6 for detailed expert assessment feedback.

3 Assessment Conclusion

The expert assessors completed the expert assessment of the draft *Estimating organic carbon stocks using digital soil mapping: calibration, validation and uncertainty estimation* and confirmed the draft methodology and proposed updates adhere to the criteria established.

4 Expert Qualifications

Jaclyn Kachelmeyer has a Masters Degree from the Yale School of the Environment. She formerly led the Agricultural Carbon team at TerraCarbon and was part of the team that developed and revised VM0042.

Dan Kane, PhD, is a director at Mad Agriculture. Dan holds a PhD from the School of Forestry and Environmental Studies at Yale and formerly worked at TerraCarbon, where he was part of the team that developed and revised VM0042. Dan has published in the fields of soil science, regenerative agriculture, and sustainability.

Brian McConkey, PhD, is the Chief Scientist for Viresco Solutions. He has over 35 years of agri-environmental research experience from roles with Alberta Ministry of Agriculture, Environment Canada, and Agriculture and Agri-Food Canada. Brian's leadership has notably influenced Canada's national greenhouse gas inventory methods and international guidance documents for reporting emissions. He has authored or co-authored more than 200 peer-reviewed journal articles and book chapters.

Sassan Saatchi, PhD, is a senior scientist at JPL-Caltech. He has published extensively on aboveground forest carbon using remote sensing and is actively involved in developing the algorithms for detecting changes in aboveground ground carbon using the NASA NISAR

Mission (a synthetic aperture radar). Sassan was a contributing author of the VCS Tool VT0005 (Tool for aboveground live forest biomass using remote sensing).

Jonathan Sanderman, PhD, is the director of the Carbon Program at Woodwell Climate Research Center. His research focuses on the role of soils in climate mitigation and sustainable food production. Jon has published numerous high-profile papers closely related to topics that underpin the legitimacy of nature-based climate solutions.

Alexandre Wadoux, PhD, is a fellow at the French National Institute for Agriculture, Food and Environment (INRAE). He is an expert in digital soil mapping and geostatistics, including error propagation and applications of machine learning.

5 Signature

Signed for and on behalf of:

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Name of signatory: Jaclyn Kachelmeyer, MEM

Date: 7/31/2025

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6 Expert Feedback

Section 2 – Summary Description			
#	**Paragraph/Topic from Draft Methodology**	**Comment**	**Developer's Response and/or Update**
1	Summary description	Include a plain-language summary to improve readability and general understanding.	A plain-language summary is provided in Section 2. Throughout the tool, the text explains DSM in comparison to existing approaches in VCS methodologies.

Section 3 – Definitions			
#	**Paragraph/Topic from Draft Methodology**	**Comment**	**Developer's Response and/or Update**
1	Confusion among VCS terms	Avoid ambiguity with VCS project terminology; consider always writing "model validation" / "project verification".	Terminology is consistent with the VCS Standard: throughout the document the tool refers explicitly to "model validation" (tool) and "project verification" (VVB) and avoids terms that could be misinterpreted in the context of VCS programs.
2	Prediction support	Add explicit definitions so that prediction support and prediction locations are distinct and unambiguous.	The tool includes definitions of "prediction support," "prediction location" and "mapped area"; these definitions clarify these concepts in the context of the tool relative to existing VCS methodologies.
3	Alignment with VCS methodologies	Ensure nomenclature consistency with VM0042 and VM0032; remove	Nomenclatural consistency has been ensured with respect to existing VCS programs and methodologies; methodology-specific jargon has been omitted.

Section 3 – Definitions			
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		methodology-specific jargon if the tool is to remain methodology-agnostic.	
4	Model architecture	Permit flexibility in model choice; do not impose a positive list of covariates, but add guard-rail language to prevent nonsensical predictors.	The tool states that any statistical or machine-learning architecture may be used in section 5. The model architecture must be justified in the DSM Model Validation Report by citing at least one peer-reviewed publication that appears in the Web of Science: Science Citation Index (which is consistent with the approach in VMD0053); there is no positive list of covariates, but the tool provides a list of peer-reviewed publications in an Appendix that provide users with a comprehensive overview of the types of model architectures and covariates that have been used successfully in digital soil mapping; guardrails are employed that align the tool with standards in VMD0053.

Section 4 – Applicability Conditions			
#	**Paragraph/Topic from Draft Methodology**	**Comment**	**Developer's Response and/or Update**
1	VCS methodology alignment	Tool should be compatible with VM0042 QA1 ("measure & model") *and* QA2 ("measure-remeasure"), with clear guidance for both, plus compatibility with current and future VM0032 versions and future ALM methodologies.	The tool is compatible with QA1 and QA2 in VM0042, and provides an illustration of the uncertainty calculation under both VM0042 version 2.1 and VM0032 version 1.0 in Appendix 6; because the quantities developed by the tool are generic statistical summaries of the type required in existing VCS methodologies (i.e. variance in the change in stock), the tool is forward-complaint with revisions to existing VCS methodologies.

Section 4 – Applicability Conditions			
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2	Rice	The tool should be compatible with rice agriculture while excluding permanently flooded areas.	Citations were included demonstrating applicability to rice agriculture, and the tool clarifies that *permanently flooded* areas are excluded, not partially or seasonally flooded areas.

Section 5 – Procedures			
#	**Paragraph/Topic from Draft Methodology**	**Comment**	**Developer's Response and/or Update**
1	Amount of variance explained	The tool must specify that R^2 is the amount of variance explained, not the square of the Pearson correlation coefficient with an equation, and must specify that R^2 can be negative.	R^2 has been explained in the tool in Equation 2. Text specifically notes that this quantity is the "amount of variance explained" and that it may be negative, unlike the square of the Pearson correlation coefficient.
2	Uncertainty	Distinguish clearly between (i) SD of individual predictions, and (ii) SE of the mean used in VCS methodologies to compute uncertainty.	The tool clearly distinguishes between the SD of individual predictions, which the tool calls "prediction error" (Equation 1), and the SE of the mean used to compute project uncertainty (Equation 7), which the tool calls the variance of the emissions removal estimate in soil. The SE is the square root of Equation 7, as demonstrated in a worked Appendix example.
3	Model validation	State explicitly that model validation is mandatory at least once every five years, even when the same calibrated model is	The tool states that model validation must occur at least once every five years, even when project proponents choose to "freeze" model parameters (as is the case

Section 5 – Procedures			
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		reused; clarify that model validation requires physical soil samples within the project area.	under VMD0053 for process-based biogeochemical models); the tool clarifies that independent sample data used for model validation must be acquired exclusively within the project area.
4	Validation criteria	Adopt three tests that mirror the requirements for validation of other types of models: (a) $R^2 > 0$; (b) ≥ 90% of independent validations fall in the 90% prediction interval (coverage); (c) mean residual not different from 0.	The tool adopts the three tests proposed by this comment. See section 5.1.
5	Validation quantity	Repeatedly validated models must be tested on absolute SOC stock at each date, with changes estimated by differencing; predicting SOC stock changes directly should not be permitted.	The tool describes model validation procedures applied to SOC stock at single points in time, and uses geostatistical methods to propagate model prediction error from point-in-time estimates to the variance of the emissions removal estimate in soil in units of CO2e.
6	Error propagation	Uncertainty calculation must include the variogram (or other spatial-covariance) term when aggregating uncertainty.	The tool states, "The contribution of spatial correlation in the variance of the SOC stock must be addressed. Project proponents may implement the methods described by Wadoux and Heuvelink (2023) using the steps below." This approach is illustrated in a worked example with computer code in Appendix 5.

Section 5 – Procedures			
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7	Calibration and validation data	Allow model calibration data outside the project area, but ensure that model validation data is exclusively within the project area; encourage flexibility in model calibration data, but stringent controls on model validation data.	The tool states, "Data from outside the project area may be used for calibration, but all data in the validation set must come from within the project area."
8	Intermediate verification events	Encourage flexibility by allowing DSM to be used between model validation events for project verification purposes. Ensure safeguards through point-in-time calibration in the absence of model validation.	The tool states, "The frequency of project verification is at the discretion of the project proponent, and model calibration or validation is required at every project verification event." The tool requires model validation at least once every five years, consistent with existing VCS standards.

Section 6 – Data and Parameters			
#	**Paragraph/Topic from Draft Methodology**	**Comment**	**Developer's Response and/or Update**
1	Parameter redundancy	Separate "parameters at validation" (model performance metrics, uncertainty parameters) from "parameters monitored" (already covered by VM0042); avoid duplication.	All data and parameters (section 6) are described under "Data and parameters available at validation"; no data or parameters are monitored that are not also available at validation, so the tool contains only "Data and parameters available at validation" to avoid duplication.

Section 6 – Data and Parameters			
#	**Paragraph/Topic from Draft Methodology**	**Comment**	**Developer's Response and/or Update**
2	Archiving requirements	All data, code, software versions and random seeds must be archived and available to IME/VVB.	Requirements to archive data, code and software are described in the tool and in the template DSM Model Validation Report (Appendix 4).

Appendices			
#	**Paragraph/Topic from Draft Methodology**	**Comment**	**Developer's Response and/or Update**
1	Flow diagram	Add diagram showing how DSM model validation events line up with VCS project validation and verification.	A flow diagram has been provided in response to this comment (see Figure 1 and Appendix 2).
2	Worked example	Provide a worked example using computer code that illustrates uncertainty calculations under the tool; this should include uncertainty deduction under VM0032 and the probability of exceedance method under VM0042	A worked example is provided in Appendix 5 that illustrates all calculations described in the tool; this worked example is written in computer code and is reproducible (as confirmed through public comments and VVB review); the worked example illustrates uncertainty calculations under VM0042 version 2.1 and VM0032 version 1.0.
3	Template model validation report	Include an Appendix that contains a sample version of the Digital Soil Mapping Model Validation Report; simulated / mock data is acceptable	An example DSM Model Validation Report has been provided as Appendix 4 in response to this comment. This Appendix is based on simulated data described in detail in the worked example in Appendix 5.
4	Example covariates and applications of DSM	Provide a curated list of references that illustrate examples of acceptable covariates, their processing, and overall application of DSM to agricultural contexts.	More than 1000 peer-reviewed academic journal articles have been written in the field of DSM with an explicit focus on SOC content, BD, or SOC stock, and how these quantities change over time. Sixteen influential publications are described in Appendix 3.

Appendices			
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			These publications include a wide range of model architectures and covariates.
5	BGCM integration	Provide guidance on how DSM predictions of SOC stocks should be used in conjunction with BGCMs.	Section 5.1.2 provides guidance on error propagation when using DSM to initialize and/or true-up a process-based biogeochemical model.