DNDC Validation Report

Prepared for: CAR

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1 Introduction

DNDC is a process-based, soil biogeochemical model designed to assess the impact of agricultural management practices on soil carbon and nitrogen dynamics (Li et al. 1992; Li et al. 1994, Li 2000). The model runs on a daily time step and is capable of simulating both aerobic and anaerobic soil conditions. The DNDC model has been applied across a wide range of agro-ecosystems globally, extensively validated and peer reviewed in over 200 peer-reviewed publications (Giltrap et al. 2010; Gilhespy et al. 2014; Yeluripati et al. 2015).

DNDC conducts a full accounting of carbon and nitrogen cycling by simulating the impacts of major ecological drivers (climate, soil, vegetation, management) on soil climate conditions, plant growth, and decomposition (Figure 1). The model is built using classical laws of physics, chemistry, and biology, as well as empirical equations generated from laboratory studies to parameterize specific biogeochemical processes.

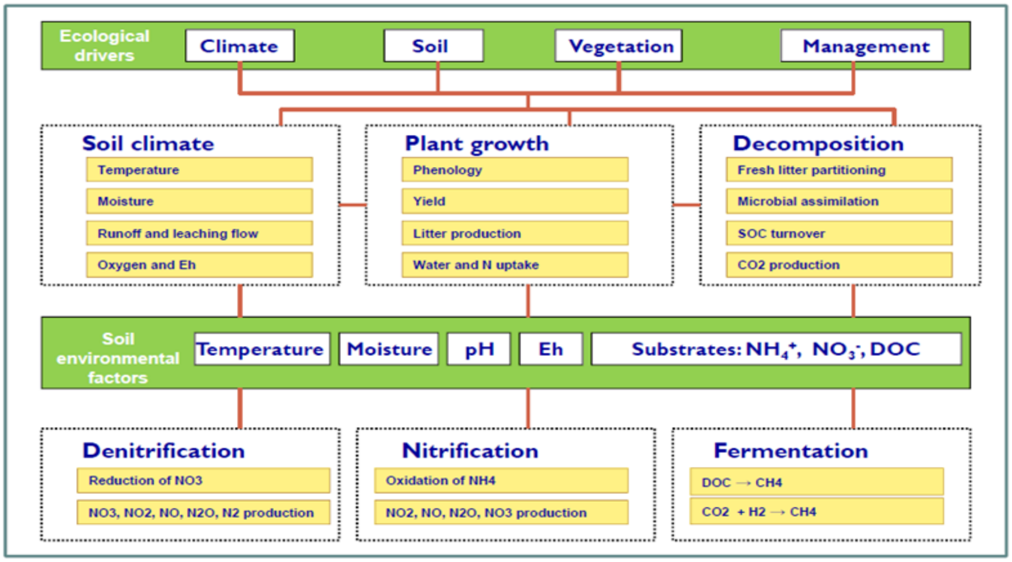

Figure 1. DNDC drivers (green boxes) and process based sub-modules (dashed boxes). Agricultural management practices directly modify the soil climate and plant growth sub-modules and indirectly alter organic matter decomposition and nutrient cycling (denitrification, nitrification, fermentation).

2 Model Calibration

2.1 Model Version

Multiple versions of DNDC have been created for research, educational, and market purposes since the model's initial development. Customized versions of DNDC have been developed for the California Air Resources Board to support their Greenhouse Gas Emission Inventory Program (Deng et al. 2017) and the Canadian government to support estimates of crop yield, GHG emissions and water quality (Smith et al. 2013). Version 9.5 of DNDC is publicly available and infrequently maintained by the University of New Hampshire. Regrow has developed the most recent version (v10.3) of DNDC under an exclusive commercial license to support the scaling of ecosystem services markets. DNDC v10.30 eliminates many bugs identified in v9.5 and ensures a daily conservation of mass for all carbon and nitrogen chemical species.

2.2 Calibration Method Description

SEP Model Requirements and Guidance define model calibration as "any process involving the adjustment of parameters and constants within a model so that the model more accurately simulates measured values." The Guidance defines parameter sets as "all values internal to a model that determine how input data drive model performance and behavior, and that are changed using processes independent of model-driving input datasets." DNDC has multiple types of input parameters that drive internal model processes. These types of input parameters include the following:

- Weather parameters
- Soil parameters
- Crop parameters
- Tillage parameters
- Fertilizer parameters
- Manure parameters
- Cutting parameters
- Grazing parameters
- Flooding parameters
- Irrigation parameters
- Plastic mulch parameters

Some model input parameters are rarely if ever measured and instead determined as a function of other, more easily measured input parameters. Appendix A lists all DNDC input parameters and their dependencies for the model version covered by this report.

The internal relationships between DNDC input parameters (the parameter sets) have not been tuned beyond the default calibration of DNDC for this validation report. This report therefore validates the default DNDC parameter set produced by decades of model research and development against measured changes in N2O emissions and SOC sequestration (Giltrap et al. 2010; Gilhespy et al. 2014). While it is possible, we did not find evidence that field data presented in our validation dataset were involved in the selection of some individual model parameters during previous research endeavors. Regrow maintains this default version of DNDC while also developing model calibration methods for future applications that are beyond the scope of this report.

2.3 Documentation of Model Parameters

All model input parameters, along with their dependencies when measurements are not available, are listed in Appendix A. A single parameter set is used throughout the entire domain validated by this report and can be shared upon request.

The observational database and computational code (model base code, processing scripts, uncertainty model code) necessary to fully reproduce the entirety of this work is permanently archived and versioned for posterity. We have demonstrated that such archiving procedure is the best method to ensure reproducibility of prior simulations. Documenting a list of model parameters that are influenced by (or in some way derivative to) a set of user inputs does not, in itself, ensure reproducibility because there may be various updates to the model base. Regular updates of the model code base are intended to improve performance, to update process-representation (e.g., a new N2O emission pathway), add simulated events (e.g., fire, erosion), or provide bug fixes. For these reasons, we regularly version and archive to ensure reproducible results and transparency of the model code base. Archived versions associated with Validation Reports or Projects are available upon request.

2.4 Data Split Process and Justification

Regrow maintains a large database of experimental studies used for regular calibration and validation of DNDC. This database is populated through literature reviews of peer-reviewed studies and datasets that report changes in emission sources of interest within targeted validation domains. Studies must report sufficient data to enable DNDC simulations to be included in the database.

The database is used to build and run DNDC simulations for relevant experimental **treatments**. Each treatment is defined by longitudinal measurements of a target emissions source (i.e. SOC stock change or N2O emissions flux) under specific management, soil, and climate conditions. Each treatment is linked to a **study** in the CALVIN database. A study represents a unique experimental design from which data is collected. Multiple publications can refer to a single study, for example the Morrow plots, established in 1876 in Urbana, Illinois, contain the oldest experimental plots in the US including the longest continuous corn plot in the world (Odell, 2015). Over time the field has been divided into sub plots studying the impact of changing fertilizer rates and forms as well as crop rotations. Multiple publications in the Regrow database report outcomes of different treatments on multiple emission sources from this single study. Each treatment is also linked to a **site** that represents a unique set of experimental fields with shared climate and soils data. One study can therefore span multiple sites (i.e. when geography or soil type is a factor of interest) but does not have to. Each treatment is therefore linked to a unique **study-site** combination.

Treatments are paired within study-sites to evaluate DNDC's ability to predict changes in emissions between treatments. This scale of model evaluation mimics the subsequent credit quantification in CAR SEP where the credit is the difference in GHG outcomes between two paired management scenarios (baseline and project). A given **treatment-pair** in Regrow's validation database may have multiple sets of measurements over the duration of the treatments (i.e. measurements at *t = 0, 5,* and *10*). In this case all possible **treatment-pair measurements** are used for model validation (3 paired measurements in the previous example, 5-0, 10-5, 10-0) (Section 3 of this report).

When both calibration and validation are needed, each study-site within the database is assigned to either the calibration or validation pool. This split is not done at random and is intended to result in complete coverage of the target validation domain by both the calibration and validation pools. The split also aims to evenly represent GHG-relevant elements of study design (i.e. length of study, depth of soil sampling) between calibration and validation pools. While study-sites are not assigned randomly to either calibration or validation pools, assignment is done prior to any model calibration and assessment to avoid biasing study-site allocation to improve model performance.

For this report - Regrow's database was split into calibration and validation pools with the intent of model calibration. However, model calibration proved unsuccessful and was abandoned, resulting in only the study-sites in the validation pool being used to validate the model (Appendix B).

3 Validating and Reporting Model Performance and Uncertainty

Validation of DNDC is demonstrated through the description of an uncertainty model, allowing for the propagation of the uncertainty quantified through the validation data to new modeling units included in the validation domain.

3.0 Description of Uncertainty Model

Regrow's uncertainty model is an empirical model that estimates the lack of fit between model estimates and measured values of differences in a given Emissions Source (ES) between two paired scenarios. A separate uncertainty model exists for each Emissions Source. In this report Regrow presents uncertainty models for both soil organic carbon (SOC) sequestration and Direct N2O emissions.

This report validates the following simple statistical model:

$$y_i = \eta_i + \delta_i + \epsilon_i$$

where y_i are the measurements of treatment-pair level differences (offsets) from the validation dataset, n_i are the DNDC model estimates of these treatment-pair level differences (offsets), δ_i is a single bias/model discrepancy estimate, and the ϵ_i's are independent random normals centered at 0 with the same single variance parameter σ, which captures the observational error and other random variability such as within field variability.

Regrow estimates the uncertainty model using a Bayesian framework to simplify the model's parameter uncertainties along with its prediction uncertainty to new modeling units. A half-Cauchy distribution with location parameter 0 and scale parameter 1 is used for the non-informative prior distribution of following a recommendation by Gelman (2006), while a Normal distribution centered at 0 with a large standard deviation of 100 is used as the prior distribution for σ. Posterior probability distributions for both parameters are sampled using Markov Chain Monte Carlo (MCMC) methods, a standard Bayesian sampling method that iteratively draws samples from approximate distributions called transition distributions, which through the use of a Markov Chain are improved with each iteration until the chain converges to the target posterior distribution (Gelman et al., 2013). Sampling is done in Stan software (Carpenter et al., 2017) using the No-U-Turn Sampler developed by Hoffman and Gelman (2014). Initial warm-up samples from each MCMC run (the so-called "burn-in") are discarded yielding a final distribution of 1000 samples. Convergence is evaluated using the Gelman-Rubin statistic, which approaches 1 as the model converges (Gelman & Rubin, 1992). Once sampled, the posterior distributions of δ and σ are used to propagate the structural uncertainty in the validation dataset to DNDC offset estimates of new fields via Monte Carlo integration.

3.1 Declare Practice Categories Requiring Evaluation

This validation report declares the practice categories listed in Table 1 valid for the specified emissions sources (ES) within the domain described in Section 3.2.

Table 1. Practice categories validated by Emissions Source within the domain described in this report. Study-sites listed in **bold font** for Direct N2O report annual emissions over a >310 day period (see also Table 8 of this report).

Practice Category	PC Code	SOC		Direct N2O	
		Study-site Key	LRR Key	Study-Site Key	LRR Key
Soil disturbance and/or residue management	TR	al-kaisi_2005a-NRDM al-kaisi_2005a-SRDF balkcom_2013-PARU clapp_2000-UMROC COFOARD1_GHG_123_SOC-ARDEC locke_2013-CPSRUF mitchell_2015_2017-wsrec MTSINVND-NVND sainju_2002-ARS sainju_2008-AAES sainju_2014a-SID_MT sanborn_field-SF	C,F,G,K,M,N,O,P	**COFOARD1_GHG_123_SOC-ARDEC** MTSINVND-NVND sainju_2014a-SID_MT COFOARD2_GHG-ARDEC **COFOARD3_GHG-ARDEC** nash_2012-GMRC parkin_and_kaspar_2006-AEARRF SDBRREAP-SDBRREAP smith_2012-SAREC wegner_2018-NCARL	F,G,M,N
Cropping practices, planting and harvesting (e.g., crop rotations, cover crops)	Crop	balkcom_2013-PARU locke_2013-CPSRUF mitchell_2015_2017-wsrec MTSINVND-NVND pikul_2008-ESDSWRF poffenbarger_2017-central sainju_2002-ARS	C,F,H,K,M,N,O,P	MTSINVND-NVND sainju_2014a-SID_MT COFOARD2_GHG-ARDEC hernandez-ramirez_2009-ACRE **mcgowan_2018-KSU_ARF** parkin_and_kaspar_2006-AEARRF	F,G,H,M

		sainju_2008-AAES sainju_2014a-SID_MT sanborn_field-SF varvel_2008-UNE_Shelton WICST-WIARS		SDBRREAP-SDBRREAP wegner_2018-NCARL	
Inorganic nitrogen fertilizer application	InN	clapp_2000-UMROC COFOARD1_GHG_123_SOC-ARDEC MTSINVND-NVND pikul_2008-ESDSWRF poffenbarger_2017-central sainju_2002-ARS sainju_2008-AAES sainju_2014a-SID_MT sanborn_field-SF varvel_2008-UNE_Shelton	F,G,H,K, M,N,P	**COFOARD1_GHG_123_SOC-ARDEC** MTSINVND-NVND COFOARD2_GHG-ARDEC **COFOARD3_GHG-ARDEC** **COFOARD4-ARDEC** engel_2010-APF fernandez_2015-CSREC hoben_2011-Mason KYBGGHG-KYBGGHG nash_2012-GMRC nash_2015-GMRC omonode_and_vyn_2013-Haubstadt parkin_and_hatfield_2010-ISURF smith_2012-SAREC	E,F,G,L, M,N
Organic amendments application	OrN	sainju_2008-AAES sanborn_field-SF	M,N*	**COFOARD4-ARDEC** hernandez-ramirez_2009-ACRE KYBGGHG-KYBGGHG smith_2012-SAREC	G,M,N

*Coverage from only two LRRs is inadequate for validation. Therefore organic amendment applications for SOC are **not** validated by this report.

Table 2. LRR Lookup Table. For maps of each LRR see this NRCS website.

Land Resource Region (LRR)	LRR Key
California Subtropical Fruit, Truck, and Specialty Crop Region	C
Rocky Mountain Range and Forest Region	E
Northern Great Plains Spring Wheat Region	F
Western Great Plains Range and Irrigated Region	G
Central Great Plains Winter Wheat and Range Region	H
Northern Lake States Forest and Forage Region	K
Lake State Fruit, Truck Crop, and Dairy Region	L
Central Feed Grains and Livestock Region	M
East and Central Farming and Forest Region	N
Mississippi Delta Cotton and Feed Grains Region	O
South Atlantic and Gulf Slope Cash Crops, Forest, and Livestock Region	P

3.2 Definition of the Model Validation Domain

Regrow's approach to validating model performance within a validation domain deviates from CAR's Guidance. In accordance with the guidance, Regrow's approach still defines a validation domain as the multidimensional space of biophysical attributes within which a model has been confronted with data. For a given emissions source (ES), these biophysical attributes include land resource regions (LRRs), crop functional groups (CFGs) and soil texture classes. However, this report does not evaluate model performance for each unique combination of attributes. Such a granular requirement for model validation greatly reduces the data available for validation and is untenable for many combinations. Instead, this report considers a single evaluation of model performance for a given emissions source (ES) across the entirety of a validation domain sufficient to validate the model. Model performance across the entire domain is described by a general uncertainty model (another deviation from the CAR Guidance, Sections 3.4 and 3.5) that allows for the propagation of any bias and error in the validation dataset to crediting simulations. This deviation has previously been presented to and approved by CAR (Appendix C).

The extent of a validation domain is defined by the dimensions of the biophysical attributes covered by the studies used to generate the validation dataset. For example, consider the domain represented by the two following hypothetical studies in Table 3.

Table 3. Hypothetical validation domain created by two studies

	Study 1	**Study 2**	**Domain for SOC (Studies 1 + 2)**	**Domain for Direct N2O (Study 2 only)**
Emissions Sources (ES)	SOC	SOC, Direct N2O	-	-
Practice Categories (PC)	soil disturbance	soil disturbance	soil disturbance	soil disturbance
Land Resource Regions (LRR)	Central Feed Grains	Lake States	Central Feed Grains, Lake States	Lake States
Crop Functional Groups (CFG)	C4 annual, C3 N-fixing	C3 annual	C4 annual, C3 N-fixing, C3 annual	C3 annual
Soil Texture Class	loam	clay loam	loam, clay loam	clay loam

3.2.1 Model validated Practice Categories and Crop Functional Groups by Emission Source

This validation report declares the crop functional groups (CFGs) listed in Table 4 valid for the specified emissions sources (ES).

Table 4. Crop functional groups validated by Emissions Source within the domain described in this report

Crop Functional Group	**CFG Code**	**SOC Study-site Key**	**Direct N2O Study-site Key**
C4, annual, non-N-fixing, herbaceous, non-flooded	C4A	al-kaisi_2005a-NRDM al-kaisi_2005a-SRDF balkcom_2013-PARU clapp_2000-UMROC COFOARD1_GHG_123_SOC-ARDEC pikul_2008-ESDSWRF poffenbarger_2017-central sainju_2002-ARS	COFOARD1_GHG_123_SOC-ARDEC sainju_2014a-SID_MT COFOARD2_GHG-ARDEC COFOARD3_GHG-ARDEC COFOARD4-ARDEC fernandez_2015-CSREC hernandez-ramirez_2009-ACRE hoben_2011-Mason

		sainju_2008-AAES sanborn_field-SF varvel_2008-UNE_Shelton WICST-WIARS	KYBGGHG-KYBGGHG mcgowan_2018-KSU_ARF nash_2012-GMRC nash_2015-GMRC omonode_and_vyn_2013-Haubstadt parkin_and_hatfield_2010-ISURF parkin_and_kaspar_2006-AEARRF SDBRREAP-SDBRREAP smith_2012-SAREC wegner_2018-NCARL
C3, annual, non-N-fixing, herbaceous, non-flooded	C3A	balkcom_2013-PARU locke_2013-CPSRUF mitchell_2015_2017-wsrec MTSINVND-NVND pikul_2008-ESDSWRF sainju_2002-ARS sainju_2008-AAES sainju_2014a-SID_MT sanborn_field-SF varvel_2008-UNE_Shelton	MTSINVND-NVND sainju_2014a-SID_MT COFOARD2_GHG-ARDEC engel_2010-APF parkin_and_kaspar_2006-AEARRF wegner_2018-NCARL
C3, annual, N-fixing,, herbaceous, non-flooded	C3AN	al-kaisi_2005a-NRDM al-kaisi_2005a-SRDF locke_2013-CPSRUF mitchell_2015_2017-wsrec MTSINVND-NVND pikul_2008-ESDSWRF poffenbarger_2017-central sainju_2002-ARS sainju_2014a-SID_MT sanborn_field-SF varvel_2008-UNE_Shelton WICST-WIARS	MTSINVND-NVND sainju_2014a-SID_MT COFOARD2_GHG-ARDEC hernandez-ramirez_2009-ACRE mcgowan_2018-KSU_ARF parkin_and_kaspar_2006-AEARRF SDBRREAP-SDBRREAP wegner_2018-NCARL
C3, annual, non-N-fixing, shrub, not-flooded	C3AS	balkcom_2013-PARU locke_2013-CPSRUF mitchell_2015_2017-wsrec sainju_2008-AAES	None
C4, perennial, non-N-fixing,herbaceou s, not-flooded	C4P	None	mcgowan_2018-KSU_ARF
C3, perennial, non-N-fixing, herbaceous, not-flooded	C3P	sanborn_field-SF	None

C3, perennial, N-fixing, herbaceous, not-flooded	C3PN	pikul_2008-ESDSWRF sainju_2002-ARS	None

3.2.2 Validated Land Resource Regions by Emission Source

See Section 3.1 (Table 1) for a list of all LRRs validated for the specified emissions sources by this report.

3.2.3 Validated Soils by Emission Source

This validation report declares the soil texture classes listed in Table 5 valid for the specified emissions sources (ES). Representative clay fractions come from Li et al. 1992 and Li et al. 2014.

Table 5. Soil texture classes validated by Emissions Source within the domain described in this report

Soil Texture Class	**Representative Clay Fraction**	**Validated GHG Pools/Gasses**
Clay	0.63	None
Sandy Clay	0.49	None
Silty Clay	0.43	None
Clay Loam	0.41	SOC, Direct N2O
Silty Clay Loam	0.34	SOC, Direct N2O
Sandy Clay Loam	0.27	SOC, Direct N2O
Loam	0.19	SOC, Direct N2O
Silt Loam	0.14	SOC, Direct N2O
Silt	N/A	None

Sandy Loam	0.09	SOC, Direct N2O
Loamy Sand	0.06	None
Sand	0.03	None

Clay range in model simulations:

- SOC: min = 6.2% (Balkcom 2013 PARU), max = 33% (COFOARD1_GHG_123_SOC ARDEC), range = 26.8%
- N2O: min = 11.9% (Smith 2012 SAREC), max = 47% (SDBRREAP), range = 35.1%

3.3 Data to Validate Model Performance and Uncertainty

3.3.1 Generalized Dataset Attributes

The validation dataset for each emissions source (ES) consists of studies reporting measurements of the emissions source of interest. For SOC, studies needed to report measurements over at least a five-year period. Measurements of bulk density were required for the initial SOC stock measurement but not for subsequent measurements. Methods of collection and analysis had to be described and consistent between treatments. All studies were focused on SOC measurements and thus removed surface litter, tree branch, wood chips, as well as larger particles before analyzing for SOC. For soils where no inorganic carbon forms are present (non-calcareous soils and soils not recently limed) the total carbon can be considered to be organic carbon. With calcareous soils, recently limed soils, or in geographic areas where parent material/geology is limestone, dolomite, or other carbonate-bearing mineral, organic carbon may be estimated as the difference between total carbon and inorganic carbon concentrations (Schumacher, 2002). The most common methods for deriving SOC within our studies were were: (1) dry combustion at high temperatures for total carbon determination on the sample (2) analysis of a soil for total carbon and inorganic carbon and subtraction of the inorganic carbon concentration for the total C content and (3) dichromate oxidation procedures, which involves oxidation of organic carbon compounds by Cr2O72- and subsequent determination of unreduced Cr2O72- by oxidation-reduction titration with Fe+2 or by colorimetric methods (Sparks et al. 2020). Depth of soil sampling within the final dataset ranged from 10 to 30 cm. The units of interest used in uncertainty quantification were annual changes in time and differences between treatments (Equation 1) in tCOe per acre per year. Treatment-pairs were required to share a common soil sampling depth and length between sampling dates.

Equation 1: Difference in treatment pair annual changes in SOC

$$dsoc_j = \frac{soc_{t_1,d_2,j} - soc_{t_1,d_1,j} - (soc_{t_2,d_2,j} - soc_{t_2,d_1,j})}{y_j}$$

where

j : treatment pair case (row id)

t_1 : treatment 1

t_2 : treatment 2

d_1 : date 1

d_2 : date 2

y : length of time in years between date 1 and date 2

For Direct N2O, studies needed to report measurements of Direct N2O emissions at a daily temporal scale over at least a full growing season (please see Appendix D for list of studies and coverage with sampling > 310 days). All n2o measurements in this validation were from either manual or automatic static chambers. Best efforts were made to eliminate studies from entering our database with infrequent sampling greater than ~1-2weeks, especially if the sampling was on a regular interval (as opposed to event-based). Completely eliminating older studies that may have followed older best practice protocols (Parkin et al., 2003 vs. 2010) would have eliminated some very valuable information. Further, since our main purpose was to compare differences between treatments and not just annual emissions we felt that we could still measure impact of treatments even when sampling was not as high density as we would have desired. Where gaps in daily data were present, linear interpolation was used to calculate seasonal Direct N2O emissions (Mishurov and Kiely, 2011). Additional requirements for studies to be included in the validation dataset are listed in Table 6. Treatment-pairs were required to share a common season/year. Units of interest for uncertainty quantification were differences between treatment pairs of total (seasonal/annual) direct N2O emissions in tCO2e per acre (Equation 2).

Equation 2: Difference in treatment pair changes in seasonal/annual Direct N2O emissions

$$\sum_{d=1}^{N} e_{dt_1} - e_{dt_2}$$

where

e : direct N2O at daily temporal scale

t_1 : treatment 1

t_2 : treatment 2

d : day number since start of measurement period within a given year

N : total number of days between the start and end dates of the common season/year of treatments 1 and 2

Table 6. Management data requirements for inclusion in validation datasets for two emissions sources (SOC and Direct N2O).

category	parameter	Direct N2O	SOC
crop	plant_date	required	can be estimated
crop	harvest_date	required *...if post-season emissions measured*	can be estimated
crop	residue_fraction	required *...for multi-year measurements*	required
tillage	till_date	required *...for events during measurement timeframe*	can be estimated
tillage	till_depth	can be estimated	can be estimated*
fertilizer	fert_date	required	can be estimated
fertilizer	fert_type	required	can be estimated
fertilizer	fert_rate	required	can be estimated
fertilizer	fert_depth	required	can be estimated
manure	manure_date	required	can be estimated
manure	manure_amount	required	required
manure	manure_cn	required	required
manure	manure_method	required	required
irrigation	irrig_date	required	can be estimated
irrigation	irrig_amount	required	can be estimated
flooding	start_date	required	can be estimated
flooding	end_date	required	can be estimated

* tillage depth can be estimated when information on the tillage implement is provided

The number of LRRs declared valid by this report is the same as the number of LRRs covered by the validation dataset (Section 3.2.2).

The extent of the single validation domain specified for each Emissions Source includes all soil texture classes covered by study-sites in the validation dataset (Section 3.2.3). The range of clay content represented within these two validation domains is roughly 10-50% clay for SOC and roughly 15-50% for Direct N2O (Section 3.2.3).

3.3.3 Special Rules for Practice Categories

There are no special rules for practice categories to consider under this report. Regrow's requested deviation results in the dissolution of CFG x PC x ES unit to only ES units. Per this request, any crop rotation of crops covered by the declared crop functional groups (Section 3.2.1) would be valid.

3.3.4 Model Initialization and Gap-filling Methods

DNDC simulations are built and run for each treatment in the validation dataset. Each simulation is initialized over a spin-up period consisting of the five years prior to the first measurement date of the Emissions Source of interest. Where the data presented in the study does not provide all necessary DNDC input parameters, simulations are gap-filled using the methods in Appendix A.

3.3.5 Studies in the Validation Dataset

All studies in the validation dataset are summarized by Emissions Source, Land Resource Region, Crop Functional Group, Practice Category, and Soil Texture Class in Appendix B.

3.4 Assessment of Bias for Each PC/CFG/ES Combination

Regrow's approach to evaluating model bias results in the following deviations from the CAR Guidance (see also Appendix C):

- Regrow estimates model bias once for each Emissions Source across the entire validation domain and not at the PC x CFG x ES level specified in the Guidance.
- The measured and modeled units of interest for Regrow's calculation of model bias are the differences in emissions for a given Emissions Source (annual dSOC or total (seasonal/annual) N2O) *between paired treatment measurements.* This is implicitly assumed but not explicitly stated in Equation 3.1 of the Guidance.
- Regrow's uncertainty model includes a model discrepancy term (Section 3.0 & Figure 2) that allows for the correction of any bias and propagation of this estimate's uncertainty to model simulations of credited fields, while the Guidance calculates bias using the empirical Equation 3.1 but does not account for it in novel crediting simulations. The model discrepancy term (delta) is similar to the bias calculation (equation 3.1) in that the posterior mean of delta is approximately the average of measured and modeled differences. Unlike in equation 3.1, it is the measured minus modeled, thus a negative value indicates that the model overestimates measured emission differences between treatment-pairs while a positive value indicates an underestimate. Furthermore, the delta parameter has no weighting by study. Tables of specific study bias using equation 3.1 are available in appendix G.

- Regrow reports a single value of pooled measurement uncertainty (PMU) by emission source based on all available treatment pairs from studies in the validation database reporting replicated variability. We compare the posterior distribution of the delta parameter for each emission source to the corresponding PMU estimate.

Histograms showing the model discrepancy parameter's posterior distribution for both SOC and Direct N2O emissions are shown in Figure 2.

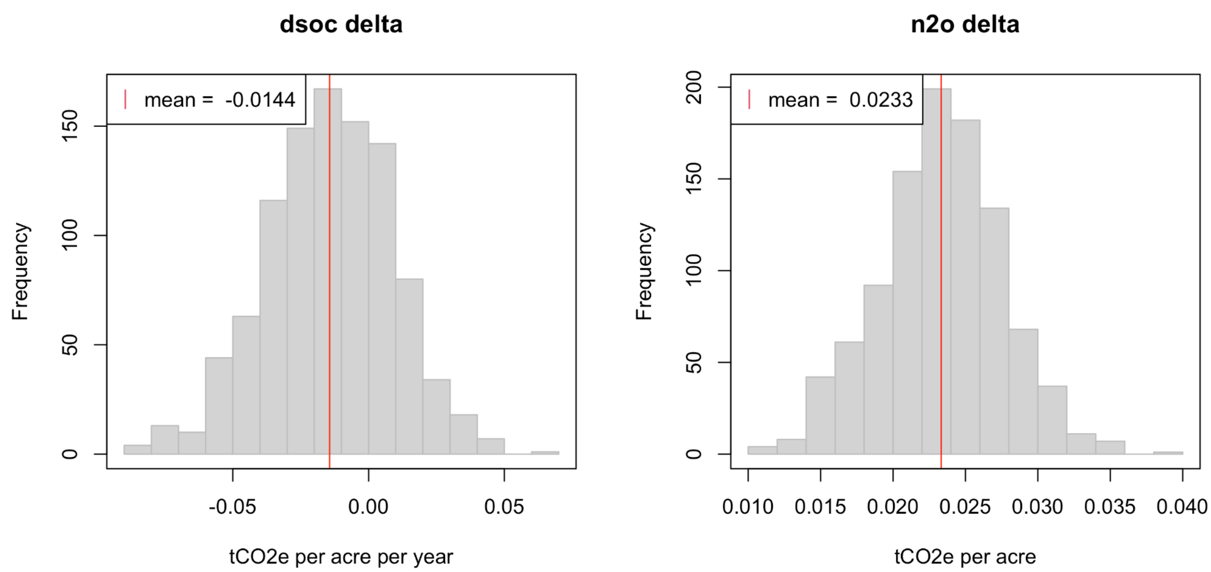

Figure 2. Posterior distributions of the model discrepancy/bias parameter of the uncertainty model by emission type based on the validation set.

PMU calculations
dSOC

Table 7 lists the studies used in the PMU calculation for dsoc. These studies report the SOC measurement error and the number of replicates used in the calculations, but not information about correlations between measurements at different times and treatments.

Table 7: Counts of dSOC treatment pairs with 5 or more years between SOC measurement from studies used for PMU calculation for dsoc by study and by those reporting standard error.

Study-site Key	**Treatment paired measurements**	**Treatment paired reporting standard error**	**Depth of measurements (cm)**
balkcom_2013-PARU	21	21	15
poffenbarger_2017-central	45	45	15

mitchell_2015_2017-wsrec	40	6	30
Sum Total	**106**	**72**	

We calculate approximate measurement errors of SOC changes based on the available information (Equation 3). We note that the example calculation of measurement errors due to practice changes (general for any emission) in Figure 3.1 of the SEP Model Guidance uses the same approximation (i.e. the variance of the difference is the sum of the variances). This approximation is exact if the two differenced quantities are uncorrelated, otherwise it overestimates.

Equation 3. Measurement error for changes in SOC tCOe2 per acre per year due to practice change

$$\sigma_j = \frac{\sqrt{\frac{\sigma^2_{t_1,d_2,j}}{n_{t_1,d_2,j}} + \frac{\sigma^2_{t_1,d_1,j}}{n_{t_1,d_1,j}} + \frac{\sigma^2_{t_2,d_2,j}}{n_{t_2,d_2,j}} + \frac{\sigma^2_{t_2,d_1,j}}{n_{t_2,d_1,j}}}}{y_j}$$

where

j : treatment pair case (row id)

σ^2 : SOC replicate variance (includes t, d and j subscripts)

t_1 : treatment 1

t_2 : treatment 2

d_1 : date 1

d_2 : date 2

n : number of replicates (includes t, d and j subscripts)

y : length of time in years between date 1 and date 2

The total number of treatment pair measurements used in the calculation was 72 of which 15 had an unbalanced number of replicates between treatments. We thus apply an additional modification to equation 3.2 of the Model Guidance where we used the largest replicate count for n_j. This results in the smallest estimate of PMU given the available information which is the most conservative threshold. Equation 4 shows the complete calculation for PMU using all 72 treatment pairs, which Table 8 gives a partial calculation for demonstration purposes. The study in table 8 (Mitchell_2015_2017, site=wsrec) measures total C and total N by combustion using a combustion C analyzer (CE Elantech, Inc., Lakewood, NJ).

Equation 4. PMU of changes in SOC tCOe2 per acre per year due to practice change

$$PMU = \sqrt{\frac{\sum_{j=1}^{72} \sigma_j^2 (n_j - 1)}{\sum_{j=1}^{72} (n_j - 1)}}$$ = 0.16 tCO2e per acre per year

where $n_j = max(n_{t_1,d_2}, n_{t_1,d_1}, n_{t_2,d_2}, n_{t_2,d_1})$.

Table 8: Example PMU Calculation

study_site	***date1***	***date2***	***y***	***sigma_t1_d1***	***sigma_t1_d2***	***n_t1_d1***	***n_t1_d2***
mitchell_2015_2017-wsrec	1999-10-17	2007-10-17	8	480	1150	8	8
mitchell_2015_2017-wsrec	1999-10-17	2007-10-17	8	480	1150	8	8
mitchell_2015_2017-wsrec	1999-10-17	2007-10-17	8	480	1150	8	8
mitchell_2015_2017-wsrec	1999-10-17	2007-10-17	8	1520	970	8	8
mitchell_2015_2017-wsrec	1999-10-17	2007-10-17	8	1520	970	8	8
mitchell_2015_2017-wsrec	1999-10-17	2007-10-17	8	1390	940	8	8

study_site	***sigma_t2_d1***	***sigma_t2_d2***	***n_t2_d1***	***n_t2_d2***
mitchell_2015_2017-wsrec	1520	970	8	8
mitchell_2015_2017-wsrec	1390	940	8	8
mitchell_2015_2017-wsrec	830	500	8	8
mitchell_2015_2017-wsrec	1390	940	8	8
mitchell_2015_2017-wsrec	830	500	8	8
mitchell_2015_2017-wsrec	830	500	8	8

study_site	***sigma***	***sigma^2***	***n-1***	***sigma^2(n-1)***
mitchell_2015_2017-wsrec	96.8669	9383.2031	7	65682.4219
mitchell_2015_2017-wsrec	92.3711	8532.4219	7	59726.9531
mitchell_2015_2017-wsrec	69.7624	4866.7969	7	34067.5781
mitchell_2015_2017-wsrec	108.8559	11849.6094	7	82947.2656
mitchell_2015_2017-wsrec	90.4654	8183.9844	7	57287.8906
mitchell_2015_2017-wsrec	85.6341	7333.2031	7	51332.4219
			total	**total**
			42	351044.5313
		PMU (kgC/ha/year) =		91.4232
		PMU (tCO2e/acre/year) =		0.1357

The range for the dsoc delta parameter from the uncertainty model is -0.084 to 0.06 with a mean value at -0.0144, which unlike the empirical bias equation in the SEP Guidance, the posterior mean being negative means the model overestimates. However in absolute value the posterior mean for delta (0.0144 tCO2e/acre/yr) is not more extreme than the PMU (0.16 tCO2e/acre/yr). In fact it is about 10 times less extreme, and we believe any overestimate of our approximate measurement errors due to lack of information about replicate correlations is not an overestimate by 10 times.

N2O

For N2O, the posterior distribution of delta is entirely positive (0.01 to 0.04 tCO2e/acre), which means that DNDC is underestimating seasonal/annual N2O emission difference between practices and therefore not larger than PMU. Recall that delta differs in sign from the SEP CAR Model Guidance equation 3.1. That said, the PMU calculation is as follows.

The PMU for differences in treatments for seasonal/annual estimates of N2O are based on 1337 treatment pairs, 434 of which span a period greater than 310 days. These come from the 9 studies reported in table 9.

Table 9: Treatment Pair count by study and length greater than 310 days used for PMU calculation of paired treatment differences in annual/seasonal N2O total emissions.

Study-Site Key	**Treatment paired measurements**	**Treatment paired measurements > 310 days**
COFOARD1_GHG_123_SOC-ARDEC	127	20
COFOARD2_GHG-ARDEC	132	0
COFOARD3_GHG-ARDEC	240	21
COFOARD4-ARDEC	760	380
engel_2010-APF	25	0
hoben_2011-Mason	15	0
mcgowan_2018-KSU_ARF	36	13
omonode_and_vyn_2013-Haubstadt	2	0
Sum Total	**1337**	**434**

The seasonal/annual N2O measurement standard errors are based on linear interpolations of the upper and lower bounds of reported error on daily n2o measurements. The paired difference variances are calculated using the seasonal/annual total emissions measurement errors (Equation 5). This is the same calculation used in the example of CAR SEP Model Guidance Figure 3.1. However, it is an approximation that overestimates the variance when treatments (baseline and practice) are correlated.

Equation 5: Measurement variance for total annual/seasonal N2O emissions due to practice change

$$\sigma_j^2 = \frac{\sigma_{t_1,j}^2}{n_{t_1,j}} + \frac{\sigma_{t_2,j}^2}{n_{t_2,j}}$$

where

j : treatment pair case (row id)

σ^2 : seasonal/annual N2O replicate variance (includes t and j subscripts)

t_1 : treatment 1

t_2 : treatment 2

n : number of replicates

Equation 6 shows the complete calculation for PMU using all 1337 treatment pairs, which Table 10 gives a partial calculation for demonstration purposes. The study in table 10 (omonode_and_vyn_2013) measures soil N2O fluxes by the vented chamber procedure (Mosier et al., 2006). Equation 6 is exactly the Model Guidance equation 3.2 since for N2O all N2O treatment pairs the replicates are balanced (i.e. $n_{t_1,j} = n_{t_2,j}$).

Equation 6: PMU of treatment pair differences between annual/seasonal N2O total emissions

$$PMU = \sqrt{\frac{\sum_{j=1}^{1337} \sigma_j^2 (n_j - 1)}{\sum_{j=1}^{1337} (n_j - 1)}}$$ = 0.0356 tCO2e per acre per year

Table 10: Example PMU Calculation

study	sigma_t1	sigma_t2	n_t1	n_t2	sigma^2	n-1	sigma^2(n-1)
omonode_and_vyn_2013	0.6391	0.85405	3	3	0.3793	2	0.7586
omonode_and_vyn_2013	0.0571	0.0761	3	3	0.0030	2	0.0060
						total	**total**
						4	0.7646
					PMU (Kg N-N2O per ha) =		0.4372
					PMU (tCO2e per acre) =		0.0737

3.5 Evaluate Model Prediction Error

Regrow's approach to evaluating model prediction error results in the following deviations from the CAR Guidance (see also Appendix C):

- Regrow provides the data summary of measured versus modeled scatterplots, histograms of residuals and mean square error statistics, and 90% prediction interval coverage probabilities over the entire validation domain by Emissions Source but not at the PC x CFG x ES level specified in the Guidance. Practice category and crop functional group are not parameters in the uncertainty model and thus the summaries by these categories would not propagate to new modeling units.
- The measured and modeled units of interest for Regrow's calculation of model prediction error are the differences in emissions for a given Emissions Source over time and *between paired treatments.* This is implicitly assumed but not explicitly stated in Section 3.5 of the Guidance.

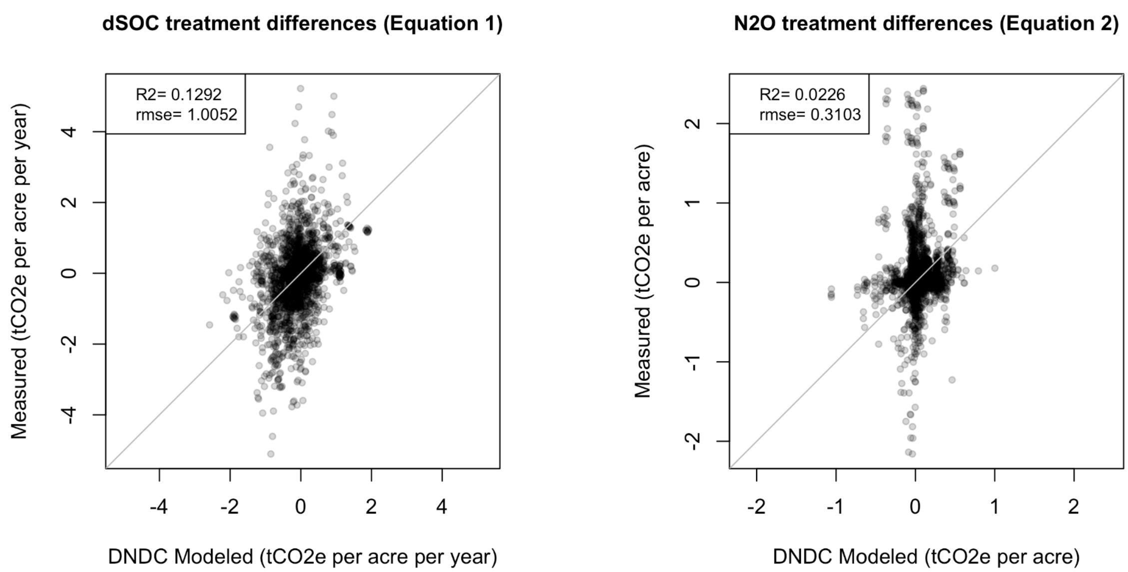

Figure 3. Scatterplots of Measured versus DNDC modeled by Emission Source for the entire validation set.

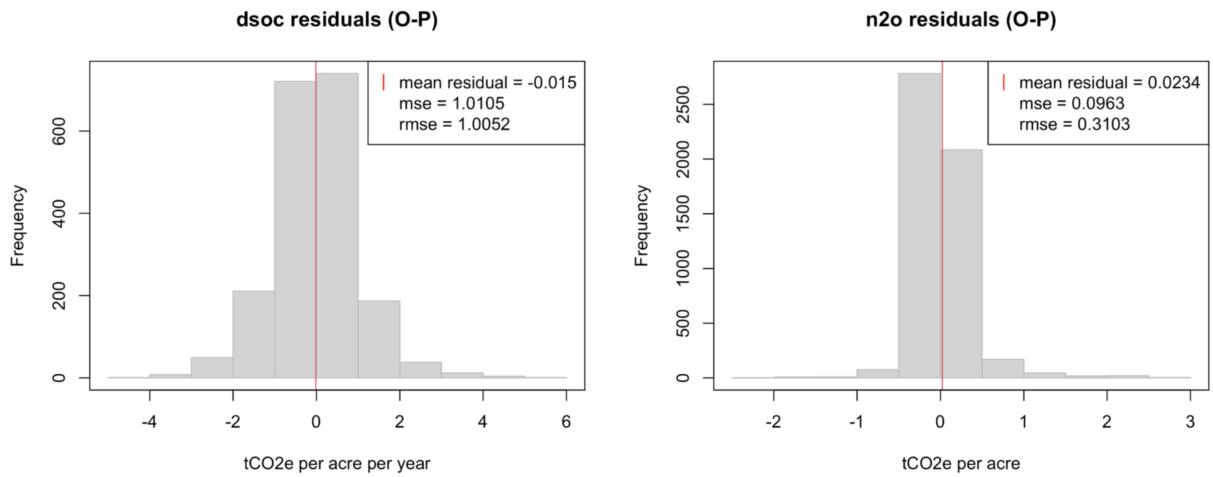

Figure 4. Histograms of residuals (measured - modeled) by Emission Source for the entire validation set.

Note in the histograms above (Figure 4) the mean residual for each emission source is approximately equal to the mean of posterior distribution of delta (Section 3.4, Figure 2) while the root mean squared error (RMSE) is approximately equal to the mean of the posterior distribution of sigma shown below (Figure 5).

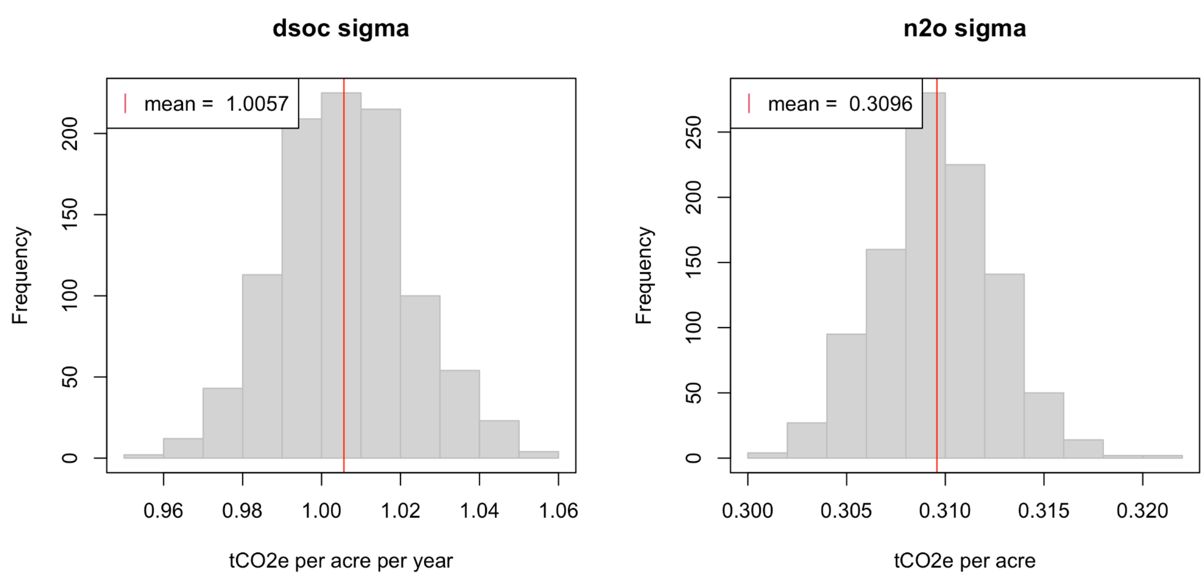

Figure 5. Posterior distributions of the sigma parameter of the uncertainty model by emission type based on the validation set.

Model prediction error is defined as the standard error of the posterior predictive distribution based on the uncertainty model. The posterior predictive distribution is the distribution of offsets at a new modeling unit not in the validation data conditional on the uncertainty model. 1000 samples are obtained from this distribution using Monte Carlo (MC) integration. To demonstrate the coverage probability of the 90% prediction intervals derived from these distributions, MC samples are obtained from posterior predictive samples at each of the modeled validation values. The number of corresponding measured validation values that fall within the 90% prediction interval is reported, and the lower and upper bounds are quantile calculations of the MC samples. For dSOC, 1771 of the total 1972 measured validation values were contained in the 90% prediction intervals (for a 89.8% coverage probability) and for N2O 4884 of the total 5219 measured validation values were contained in the 90% prediction intervals (for a 93.6% coverage probability) (Figure 6).

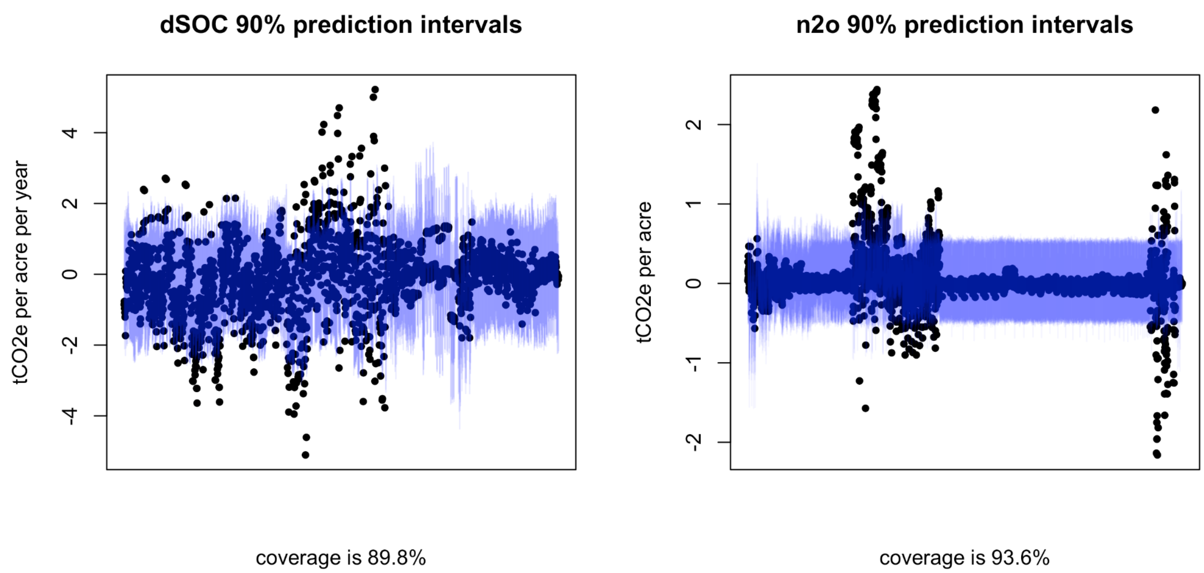

Figure 6. Measured validation values (dots) compared with 90% prediction interval (blue).

We also present model prediction error for dSOC as a function of both study-site and depth of soil measurements (Figure 7). This figure shows that model prediction error is more so a function of study-site than measurement depth across the domain, justifying the inclusion of soil measurements to <30 cm depth in the validation pool. Furthermore, there is no evidence that dSOC measurements at shallow depths (<30 cm) overestimate change in SOC relative to measurements at deeper depths (30 cm) (Appendix E).

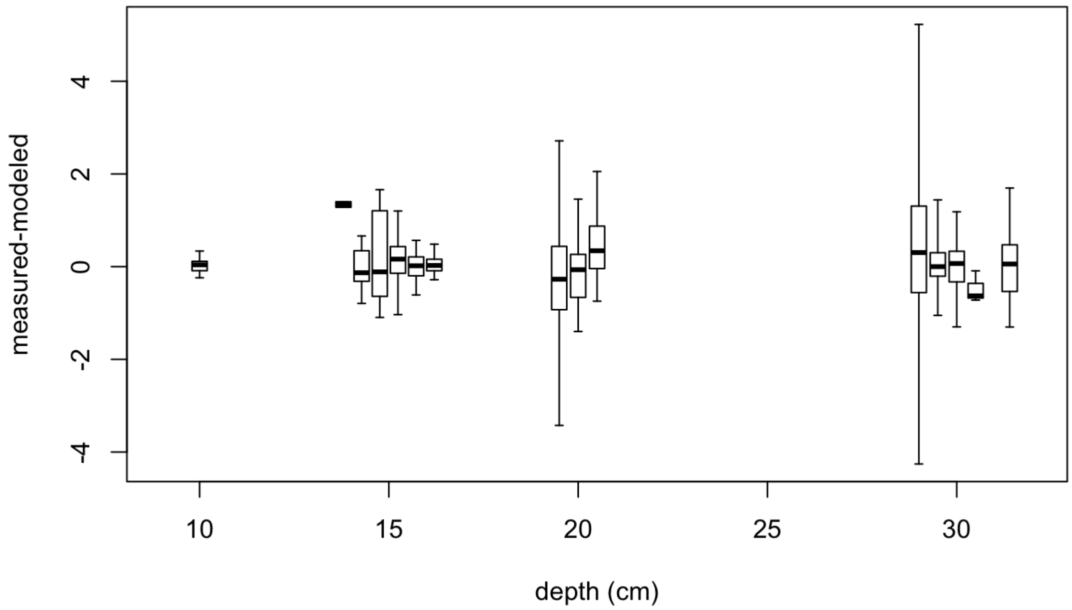

Figure 7. Model prediction error (measured - modeled) for dSOC between treatment pairs as a function of study-site (boxes) and measurement depth.

3.6 Extension of Uncertainty Model to Soil Enrichment Protocol

Regrow's deviation from the CAR SEP Guidance necessitates an additional deviation from the CAR SEP with regards to methods used to propagate model structural uncertainty from validation data to novel simulations of project fields. In particular, SEP Appendix D specifies (page 116) that "the estimate of total emissions reduction is made using measurements and model predictions on a subset of the project selected through a random sample," and thus that the sampling error is included in the quantification.

Regrow's deviation requires that model predictions be done at a sampling unit defined as a field (a contiguous area in which management practices are homogenous) and that model predictions will be made for all sampling units (fields) included in the project. This definition of the sample unit as a field is allowed by the protocol (given as an example on page 31 section 5), so when model predictions are obtained for all sample units there is no additional sampling error.

Under this deviation, Regrow will still take model input measurements of soil parameters such as initial soil organic carbon at each sample unit (field), and the average value will be used as model input. This follows the methods used in the construction of the validation data from literature studies to develop the model prediction errors, as studies commonly only report field level averages of initial soil parameters.

Quantification of field and project-level assets and uncertainty would proceed using the following process:

1. A deterministic credit value for the ES is calculated as the difference between outputs from two DNDC simulations (project - baseline for SOC, baseline - project for Direct N2O).
2. For each value of δ and σ, a single credit value is sampled from a normal distribution with **mean =** deterministic credit value + δ and **standard deviation =** σ. This is Monte Carlo integration that obtains 1000 values (one for each value of δ and σ) samples from a field-level posterior predictive distribution.
3. The samples for each field are added together across all fields in a project, resulting in a final sample of 1000 credit values that represent the project-level uncertainty distribution for the given ES.

The uncertainty deduction calculated in Equation 5.1 of the CAR SEP can be calculated using the project-level uncertainty distribution. Because this report describes an uncertainty model for Direct N2O as well as SOC, uncertainty deductions for N2O emissions reductions can be calculated along with deductions for SOC removals. In order to calculate the emissions reduction from soil organic carbon across a project in a given year, this approach necessitates a modification to CAR SEP Equation 5.3:

$$\Delta CO2\_soil_t = \Delta SOC_\mu \times (1 - UNC_t)$$

Where:
$\Delta CO2\_soil_t$ = Carbon dioxide emission reductions from the soil organic carbon pool across the project during cultivation cycle *t* (tCO2e)
ΔSOC_μ = Average change in carbon stocks in the soil organic carbon pool *between project and baseline scenarios* across the project during cultivation cycle *t* (tCO2e)
UNC_t = Uncertainty in cultivation cycle *t* (Equation 5.1)

4 Substitution for Missing Crops

No crop parameters were substituted with alternative crop parameters for this validation.

5 Verification of Model Usage

Not applicable.

6 References

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7 Appendices

Appendix A: DNDC Parameterization for Default Calibration

Category	Parameter	Description	Units	Dependency for Default Calibration	Gap-filling Data Source	Gap-filling Method
Weather	Min_temp	Minimum daily air temperature	Celsius	User provided	PRISM	Download for years of interest
Weather	Max_temp	Maximum daily air temperature	Celsius	User provided	PRISM	Download for years of interest
Weather	Precip	Daily precipitation	mm	User provided	PRISM	Download for years of interest
Soil	Texture_id	Soil texture ID	string	User provided	SSURGO	Download for geography of interest
Soil	Bulk_density	Bulk density	g/cm3	User provided	SSURGO	Download for geography of interest
Soil	ph	pH	pH	User provided	SSURGO	Download for geography of interest
Soil	Clay_fraction	Clay_fraction	Fraction	User provided or function of texture_id	SSURGO	Download for geography of interest
Soil	Porosity	Fraction of void space	Fraction	Function of Texture_id	N/A	
Soil	Field_capacity	Field capacity	WFPS	Function of texture_id	N/A	

Soil	Wilting_poitn	Wilting point	WFPS	Function of texture_id	N/A	
Soil	Hydro_conductivity	Hydraulic conductivity	m/h	Function of texture_id	N/A	
Soil	Top_layer_soc	Initial SOC fraction	Fraction	User provided	SSURGO	Download for geography of interest
Soil	Frac_litter	SOC litter fraction	Fraction	Function of texture_id	N/A	
Soil	Frac_humads	SOC humads fraction	Fraction	Function of texture_id	N/A	
Soil	Frac_humus	SOC humus fraction	Fraction	Function of texture_id	N/A	
Soil	Adjusted_litter_factor	Litter decomposition rate adjusting factor	Fraction	Function of texture_id	N/A	
Soil	Adjusted_humads_factor	Humads decomposition rate adjusting factor	Fraction	Function of texture_id	N/A	
Soil	Adjusted_humus_factor	Humus decomposition rate adjusting factor	Fraction	Function of texture_id	N/A	
Soil	cn_humads	Humads C:N	Ratio	Function of texture_id	N/A	
Soil	cn_humus	Humus C:N	Ratio	Function of texture_id	N/A	
Soil	Frac_passive_c	Passive C fraction	Fraction	Function of texture_id	N/A	

Soil	cn_passive_c	Passive C C:N	Ratio	Function of texture_id	N/A	
Soil	soc_profile_a	Depth of uniform SOC	cm	User provided	SSURGO	Download for geography of interest
Soil	soc_profile_b	SOC decrease rate	Numeric	Derived from validation data where multiple soil profiles reported. Otherwise, defaulted to 1.5.	N/A	
Soil	Initial_nitrate_ppm	Initial soil nitrate	ppm	Function of texture_id	N/A	
Soil	initial_ammonium_ppm	Initial soil ammonium	ppm	Function of texture_id	N/A	
Soil	microbial_index	Microbial activity index	fraction	Function of texture_id	N/A	
Soil	watertable_depth	Depth to water table	m	2 m	N/A	
Crop	name	DNDC crop name	NA	user provided	N/A	
Crop	crop_id	DNDC crop id	index	user provided	CDL	Downloaded for geography of interest
Crop	plant_date	planting date	date	user provided	NASS	Downloaded for state x crop of interest
Crop	end_date	crop termination	date	user provided	NASS	Downloaded for state x

		date (if not harvested)				crop of interest
Crop	harvest_date	harvest date	date	user provided	NASS	Downloaded for state x crop of interest
Crop	residue_fraction	fraction of plant remaining on soil surface after harvest	fraction	user provided	NASS	Downloaded for state x crop of interest
Crop	max_biomass	Potential maximum biomass	kgC/ha	Function of crop_id	N/A	
Crop	frac_leaf	Leaf fraction	fraction	Function of crop_id	N/A	
Crop	frac_shoot	Stem fraction	fraction	Function of crop_id	N/A	
Crop	frac_root	Root fraction	fraction	Function of crop_id	N/A	
Crop	frac_grain	Grain fraction	fraction	Function of crop_id	N/A	
Crop	cn_leaf	Leaf C:N	ratio	Function of crop_id	N/A	
Crop	cn_stem	Stem C:N	ratio	Function of crop_id	N/A	
Crop	cn_root	Root C:N	ratio	Function of crop_id	N/A	
Crop	cn_grain	Grain C:N	ratio	Function of crop_id	N/A	

Crop	tdd	Temperature degree days maturity	Degree-days	Function of crop_id	N/A	
Crop	optimum_temperature	Optimal temperature	Degrees Celsius	Function of crop_id	N/A	
Crop	water_demand	Water use efficiency	g H2O / g DM	Function of crop_id	N/A	
Crop	n_fixation_index	N fixation index (plant N / N from soil)	ratio	Function of crop_id	N/A	
Crop	vascularity_index	Vascularity index	index	Function of crop_id	N/A	
Crop	is_cover_crop	Cover crop flag	boolean	Function of crop_id	N/A	
Crop	is_perennial_crop	Perennial crop flag	boolean	Function of crop_id	N/A	
Tillage	till_date	Tillage date	date	User provided	OpTIS + internal logic	Available upon request
Tillage	till_depth	Tillage depth	cm	User provided	Regrow lit review	Available upon request
Tillage	invert	Tillage inversion	boolean	User provided	Regrow lit review	Available upon request
Fertilizer	fert_date	Date of fertilizer application	date	User provided	ERS ARMS	Downloaded for state x crop of interest
Fertilizer	fert_id	DNDC fertilizer ID	string	User provided	ERS ARMS	Downloaded for state x crop of interest

Fertilizer	fert_rate	Rate of fertilizer application	kg / ha	User provided	ERS ARMS	Downloaded for state x crop of interest
Fertilizer	fert_method	Fertilizer application method (surface/injected)	string	User provided	ERS ARMS	Downloaded for state x crop of interest
Fertilizer	fert_depth	Depth of fertilizer injection	cm	User provided	ERS ARMS	Downloaded for state x crop of interest
Fertilizer	nitrate	Fertilizer nitrate content	fraction	Function of fert_id	N/A	
Fertilizer	ammonia	Fertilizer ammonia content	fraction	Function of fert_id	N/A	
Fertilizer	ammonium_bicarbonate	Fertilizer ammonium bicarbonate content	fraction	Function of fert_id	N/A	
Fertilizer	urea	Fertilizer urea content	fraction	Function of fert_id	N/A	
Fertilizer	anh	Fertilizer anhydrous ammonia content	fraction	Function of fert_id	N/A	
Fertilizer	ammonium	Fertilizer ammonium content	fraction	Function of fert_id	N/A	
Fertilizer	sulfate	Fertilizer sulfate content	fraction	Function of fert_id	N/A	

Fertilizer	cr	Controlled release fertilizer	boolean	Function of fert_id	N/A	
Fertilizer	cr_duration	Number of days for uniform release of cr fertilizer	days	Function of fert_id	N/A	
Fertilizer	ni	Nitrification inhibitor fertilizer	boolean	Function of fert_id	N/A	
Fertilizer	ni_duration	Number of days for reduced nitrifying activity by ni fertilizer	days	Function of fert_id	N/A	
Fertilizer	ni_efficiency	Fraction of nitrifying activity inhibited by ni fertilizer	fraction	Function of fert_id	N/A	
Fertilizer	ui	Urease inhibitor fertilizer	boolean	Function of fert_id	N/A	
Fertilizer	ui_duration	Number of days for reduced urease activity by ui fertilizer	days	Function of fert_id	N/A	
Fertilizer	ui_efficiency	Fraction of urease activity inhibited by ui fertilizer	fraction	Function of fert_id	N/A	

Manure	manure_date	Date of manure application	date	User provided	Regrow lit review	Available upon request
Manure	manure_id	DNDC manure ID	string	User provided	Regrow lit review	Available upon request
Manure	manure_rate	Rate of manure application	kg / ha	User provided	Regrow lit review	Available upon request
Manure	manure_method	Method of manure application (broadcast, injected, incorporated)	string	User provided	Regrow lit review	Available upon request
Manure	manure_depth	Depth of manure application (if injected or incorporated)	cm	User provided	Regrow lit review	Available upon request
Manure	manure_cn	Manure C:N ratio	ratio	Function of manure_id	N/A	
Manure	manure_org_n	Manure organic N content	fraction	Function of manure_id	N/A	
Manure	manure_nh4	Manure ammonium content	fraction	Function of manure_id	N/A	
Manure	manure_no3	Manure nitrate content	fraction	Function of manure_id	N/A	
Cutting	cut_date	Date of cutting	date	User provided	Regrow lit review	Available upon request

Cutting	cut_fraction	Fraction of aboveground biomass cut	fraction	User provided	Regrow lit review	Available upon request
Grazing	start_date	Start date of grazing event	date	User provided	No grazing data in this report	
Grazing	end_date	End date of grazing event	date	User provided	No grazing data in this report	
Grazing	grazer_id	DNDC grazing animal ID	string	User provided	No grazing data in this report	
Grazing	heads	Number of grazing animals during event	integer	User provided	No grazing data in this report	
Grazing	hours	Hours per day spent grazing	integer	User provided	No grazing data in this report	
Grazing	additional_feed_per_head	Supplemental feed per head	kg C / head	User provided	No grazing data in this report	
Grazing	feed_cn	Feed C:N ratio	ratio	User provided	No grazing data in this report	
Grazing	excreta_removal	Was manure removed	boolean	User provided	No grazing data in this report	
Flooding	start_date	Start date of flooding event	date	User provided	Internal logic	Plant date + 30 days
Flooding	end_date	End date of flooding event	date	User provided	Internal logic	Harvest date - 21 days

Flooding	flood_water_n	Flood water N rate	kg N / ha	User provided	Regrow lit review	Available upon request
Flooding	water_leak_rate	Field water loss rate	mm / day	User provided	Regrow lit review	Available upon request
Flooding	water_gether_index	Field watershed area	hectares	User provided	Regrow lit review	Available upon request
Irrigation	irrig_date	Irrigation date	date	User provided	MIRAD	Downloaded for geography of interest
Irrigation	irrig_method	Irrigation method (flood, sprinkler, drip)	string	User provided	Internal logic	Sprinkler method
Irrigation	irrigation_index	Water deficit met by automatic irrigation	fraction	Function of irrig_date	N/A	
Plastic Mulch	start_date	Plastic mulch event start date	date	User provided	No plastic mulch gap-filling needed	
Plastic Mulch	end_date	Plastic mulch event end date	date	User provided	No plastic mulch gap-filling needed	
Plastic Mulch	cover_fraction	Fraction of field covered by plastic mulch	fraction	User provided	No plastic mulch gap-filling needed	

Appendix B: Studies in the Validation Dataset

Study-site Key	DOIs	Emissions Sources	Land Resource Region	Crop Functional Groups	Practice Categories	Soil Texture Classes	# of Treatment Pair Measure ments
al-kaisi_2005a-NRDM	10.1016/j.agee.2004.08.002 10.1016/j.apsoil.2005.02.014 10.2134/jeq2005.0437	SOC	M	C4A, C3AN	TR	loam	1
al-kaisi_2005a-SRDF	10.1016/j.agee.2004.08.002 10.1016/j.apsoil.2005.02.014 10.2134/jeq2005.0437	SOC	M	C4A, C3AN	TR	silty clay loam	1
balkcom_2013-PARU	ISBN 978-1-888626-12-4 10.2136/sssaj2013.01.0034 ISBN 978-1-888626-18-6	SOC	P	C3A, C4A, C3AS	TR, Crop	sandy loam	21
clapp_2000-UMROC	10.2136/sssaj2004.1366 10.1016/S0167-1987(00)00110-0 10.1016/S0167-1987(00)00139-2	SOC	K	C4A	InN, TR	silt loam	449
COFOARD1_GHG_123_SOC-ARDEC	doi.org/10.2134/jeq2008.0517 10.2136/sssaj2012.0413 10.2134/agronj2011.0102 10.2134/jeq2007.0268 10.2134/jeq2011.0194 10.2134/agronj2010.0455 10.2134/jeq2005.0232 https://doi.org/10.15482/USDA.ADC/1503969 https://doi.org/10.15482/USDA.ADC/1503997 https://doi.org/10.15482/USDA.ADC/1503998	SOC, Direct N2O	G	C4A	InN, TR	clay loam	82 - SOC 127 - N2O
locke_2013-CPSRUF	10.2136/sssaj2012.0325	SOC	O	C3A, C3AN, C3AS	TR, Crop	silt loam	10
mitchell_2015_2017-wsrec	10.2134/agronj14.0415 10.1016/j.still.2016.09.001 https://anrcatalog.ucanr.edu/pdf/8208.pdf - publication 8208 10.3733/ca.v060n03p146	SOC	C	C3A, C3AN, C3AS	TR, Crop	sandy clay loam	40
MTSINVND-NVND	10.1016/j.jenvman.2007.07.012	SOC, Direct	F	C3A, C3AN	InN, TR, Crop, h2o	sandy loam	630 - SOC 2520 - N2O

	10.1016/j.still.2011.10.020 Sainju 2006 workshop/AgAirQuality2006.1086 10.2134/jeq2006.0392 10.2136/sssaj2013.12.0514 10.2136/sssaj2009.0447 10.2134/jeq2012.0176 10.2134/jeq2013.10.0405 Sainju (2020) MTSINVND USDA dataset	N2O					
pikul_2008-ESDSWRF	10.1016/S0167-1987(01)00174-X 10.2134/agronj2004.0263 10.2136/sssaj2005.0334 10.2136/sssaj2008.0020	SOC	M	C3A, C4A, C3AN, C3PN	InN, Crop	sandy clay loam	36
poffenbarger_2017-central	10.1371/journal.pone.0172293	SOC	M	C4A, C3AN	InN, Crop	loam	45
sainju_2002-ARS	10.1016/S0167-1987(01)00244-6	SOC	P	C3A, C4A, C3AN, C3PN	InN, TR, Crop	sandy loam	198
sainju_2008-AAES	10.2134/agronj2000.925992x 10.2134/agronj2000.9251000x 10.2134/agronj2004.1641 10.1016/j.agee.2008.04.006	SOC	N	C3A, C4A, C3AS	InN, OrN, TR, Crop	silt loam	66
sainju_2014a-SID_MT	10.2134/agronj14.0026 10.2136/5ssaj2012.0076 10.2136/sssaj2013.08.0325	SOC, Direct N2O	F	C3A, C3AN - SOC C3A, C4A, C3AN - N2O	InN, TR, Crop - SOC TR, Crop - N2O	loam	15 - SOC 60 - N2O
sanborn_field-SF	10.1201/9780367811693 10.1081/CSS-120024062 10.22004/ag.econ.257842 10.2134/agronj2010.0221s 10.1007/s00374-002-0500-6 Motavalli and Miles (2002) Better Crops, 86(3), pp.20-23. 10.1007/s10533-013-9868-7	SOC	M	C3A, C4A, C3AN, C3P	InN, OrN, TR, Crop	silt loam + clay loam	270
varvel_2008-UNE_Shelton	10.2134/agronj2007.0383 10.2134/agronj2003.1220	SOC	H	C3A, C4A, C3AN	InN, Crop	silt loam	105
WICST-WIARS	10.2134/agronj2007.0058 10.1017/S0889189300006238 10.1016/j.agee.2012.08.011	SOC	K	C4A, C3AN	Crop	silt loam	3
COFOARD2_GHG-ARDEC	10.2136/sssaj2009.0072	Direct N2O	G	C3A, C4A, C3AN	InN, TR, Crop	clay loam	132

COFOARD3_GHG-ARDEC	10.2134/jeq2012.0129	Direct N2O	G	C4A	InN, TR	clay loam	240
COFOARD4-ARDEC	10.2134/jeq2015.08.0426 10.2134/agronj2015.0402 https://doi.org/10.15482/USDA.ADC/1503970	Direct N2O	G	C4A	InN, OrN	clay loam	760
engel_2010-APF	10.2134/jeq2009.0130	Direct N2O	E	C3A	InN	silt loam	30
fernandez_2015-CSREC	10.2134/jeq2013.12.0496	Direct N2O	M	C4A	InN	silt loam + sandy clay loam	18
hernandez-ramirez_2009-ACRE	10.2134/jeq2007.0565	Direct N2O	M	C4A, C3AN	OrN, Crop	sandy clay loam	20
hoben_2011-Mason	10.1111/j.1365-2486.2010.02349.x	Direct N2O	L	C4A	InN	sandy loam	15
KYBGGHG-KYBGGHG	10.2134/jeq2011.0197 10.2134/agronj2013.0087 https://doi.org/10.15482/USDA.ADC/1503968	Direct N2O	N	C4A	InN, OrN	silty clay loam	1053
mcgowan_2018-KSU_ARF	10.2134/agronj2018.03.0187 10.2134/agronj2018.03.0172 10.2134/agronj2009.0462	Direct N2O	H	C4A, C3AN, C4P	Crop	silt loam	36
nash_2012-GMRC	10.2136/sssaj2011.0296 10.1007/s10457-010-9362-3	Direct N2O	M	C4A	InN, TR	silt loam	20
nash_2015-GMRC	10.2489/jswc.70.4.267	Direct N2O	M	C4A	InN	silt loam	12
omonode_and_vyn_2013-Haubstadt	10.2134/agronj2013.0184	Direct N2O	M	C4A	InN	silt loam	2
parkin_and_hatfield_2010-ISURF	10.1016/j.agee.2009.11.014	Direct N2O	M	C4A	InN	silty clay loam	2
parkin_and_kaspar_2006-AEARRF	10.2134/jeq2005.0183	Direct N2O	M	C3A, C4A, C3AN	TR, Crop	sandy clay loam	30
SDBRREAP-SDBRREAP	doi:10.2136/sssaj2011.0421 10.1007/s12155-014-9413-0 10.2136/sssaj2011.0420 10.1007/s12155-016-9754-y Lehman(2020) USDA	Direct N2O	M	C4A ,C3AN	TR, Crop	silty clay loam	30

	SDBRREAP Dataset						
smith_2012-SAREC	10.1016/S1002-0160(12)60045-9	Direct N2O	N	C4A	InN, OrN, TR	sandy loam	28
wegner_2018-NCARL	10.2134/jeq2018.03.0093	Direct N2O	M	C3A, C4A, C3AN	TR, Crop	silty clay loam	84

Appendix C: Deviation Request Email correspondence with CAR

From: SamiOsman <sosman@climateactionreserve.org>
Sent: Friday, October 22, 2021 4:17 PM
To: bill@regrow.ag
Cc: Beatriz Zavariz <bzavariz@climateactionreserve.org>
Subject: RE: DNDC model validation report

Hi Bill,

I hope you're well.

My sincere apologies for taking so long to get back to you. Bety and I have been carefully considering the issues raised in your email and would like to provide the following guidance:

We are writing to update you on Regrow's progress validating the DNDC model under the Reserve's Soil Enrichment Protocol. Attached you will find two versions (short and long) of Regrow's recent model validation report. The report is intended to meet SEP requirements for model calibration, validation, and uncertainty when feasible and document Regrow's alternative approach when SEP requirements are not feasible. Our report differs from SEP requirements in the following ways:

- We have validated DNDC and evaluated its bias and uncertainty for both soil organic carbon (SOC) and nitrous oxide (N2O) over a single validation domain comprising multiple Land Resource Regions, Practice Categories, and Crop Functional Groups. We do not evaluate model bias and pooled measurement uncertainty for specific combinations of LRRs, PCs, and CFGs as there is insufficient data at this fine resolution. SO: The Reserve approves this approach to evaluating bias and pooling measurement uncertainty, provided the methodology is outlined clearly in the validation report, and it's use in this manner is approved by the independent expert reviewing the validation report.

- We use an Uncertainty Quantification methodology that leverages Monte Carlo methods to propagate model structural uncertainty from validation data to novel simulations of project fields. This approach follows the deviation request to Verra's VM0042 methodology that is currently under review. SO: The Reserve approves the use of this uncertainty quantification methodology, leveraging Monte Carlo methods, provided the methodology is outlined clearly in the validation report, and it's use in this manner is approved by the independent expert reviewing the validation report.

We have the following questions about the process for the Reserve reviewing and hopefully approving our report. Specifically:

- Regrow is not a project developer and instead aims to provide our technical expertise in biogeochemical modeling as a service to project developers. How can we therefore find a way to work directly with CAR and your science advisors to adopt/approve our approach to modeling projects under SEP? SO: Continue to engage directly with Reserve staff via email (direct all enquiries to Bety Zavariz). Reserve staff will provide direction accordingly.

- Our report is a generalized report of model performance not tied to any specific project (Option 2 in Section 3.6 of the SEP Model Requirements and Guidance document). What steps are necessary for CAR to approve such a report without tying it to a specific project? SO: The report will need to undergo review and approval by the independent expert chosen by REGROW and approved by the Reserve following a Conflict Of Interest review. The report will then come to the Reserve for final review.

- Our methods are under active development to improve overall accuracy and to provide more targeted evaluation of our ability to simulate the carbon/GHG effects of specific agricultural practices. How would CAR approval proceed in the future when (i) model developments occur (such as a new ability to simulate tile drainage practices, or changes are made to how tillage is modeled), or (ii) when the calibration/uncertainty algorithm is updated for improvement, or (iii) when new observational data are added to the validation dataset? SO: Continue to engage directly with Reserve staff via email (direct all enquiries to Bety Zavariz). Reserve staff will provide direction accordingly. It may be the certain of these changes necessitates a further review and approval by an independent expert approved by the Reserve.

Please note that the Reserve is in the midst of scoping an update to the SEP, which will likely include updates with respect to calculating uncertainty. Going forward you will be in very good hands with Bety. Bety was instrumental in developing some of the most complex aspects of this protocol and many of our protocols. Please do feel free to reach out anytime to Bety to talk through the above.

Thanks again for all your assistance with this work to date Bill. I wish you all the best.

Cheers.

Sami Osman

Policy Director |

Climate Action Reserve, a California Offset Project Registry

818 West 7th Street, Suite 710

Los Angeles, CA 90017

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Appendix D: Domain coverage for near full year N20 Studies

The aim of study selection was not to cover only the full growing season but make sure we at least covered the full growing season. Below we have included a table showing the required coverage of texture (clay), LRR, as well as all PCs and CFGs using a requirement of 310 day coverage.

Study-sites > 310 days of coverage	LRR	Texture	PC	CFG
COFOARD1_GHG_123_SOC-ARDEC	M	clay loam	InN, TR	C4A
COFOARD3_GHG-ARDEC	G	clay loam	InN, TR	C4A
COFOARD4-ARDEC	G	clay loam	InN, OrN	C4A
mcgowan_2018-KSU_ARF	G	silt loam	Crop	C4A, C3AN, C4P
parkin_and_hatfield_2010-ISURF	H	silty clay loam	InN	C4A
parkin_and_kaspar_2006-AEARRF	M	sandy clay loam	TR, Crop	C3A, C4A, C3AN

Additionally we highlight that our database includes more studies in our database that covered periods outside of just the growing season but were less than the ~10 month filter we imposed above. For example the Brookings, SD study site SDBBREAP had ~8 months of coverage that clearly showed measurements beyond the typical planting and harvest period which was ~5-6mo of the year. In this study " Sampling was discontinued during periods where installation of the chambers on the collars would have necessitated disturbance of snow cover causing a non representative sampling location"

Appendix E: Measured Treatment Effects on SOC vs Measurement Depth

Some literature suggests that positive changes in SOC at shallow depths (<30 cm) can be offset by losses at deeper depths (30 cm and deeper) (Chenu et al. 2019). Inclusion of studies measuring SOC only at shallow depths may therefore overestimate changes in SOC to the 30 cm depth required by CAR SEP. However, studies sampling at shallow depths may provide data necessary to extend a model's validation domain. Regrow's validation database was analyzed to determine the impact of measurement depth on treatment-paired differences in dSOC (Figure 1). A negative relationship between depth and treatment-paired difference would indicate overestimates at shallow depths necessitating removal of those studies from the validation dataset.

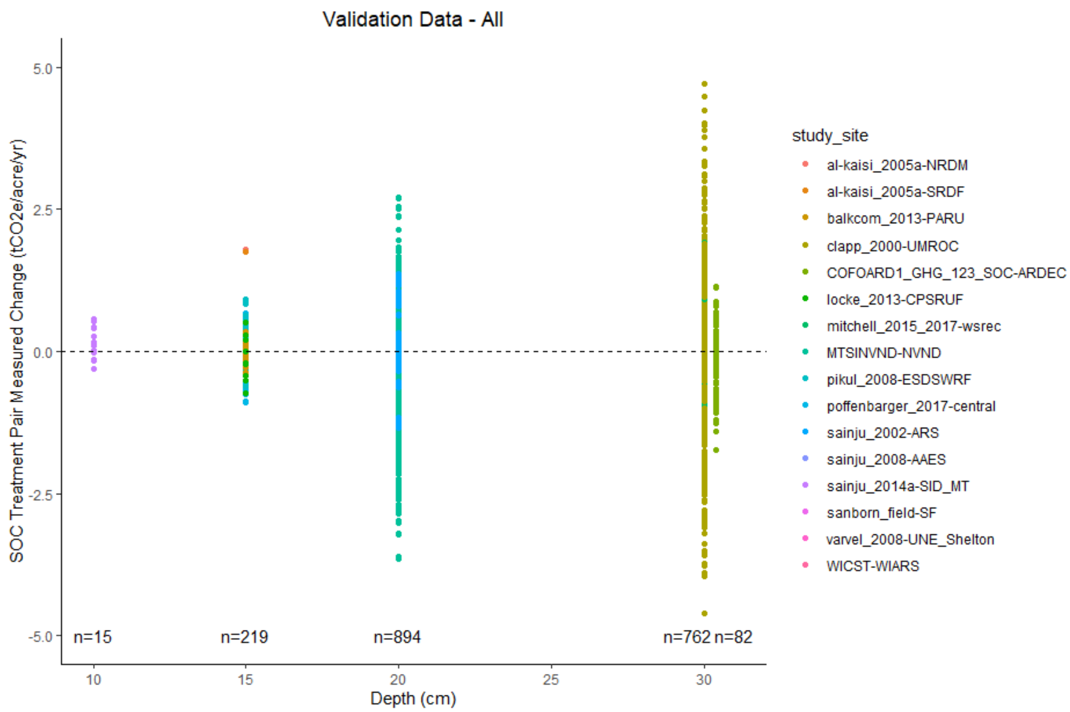

Figure 1. Measured change in SOC treatment-pairs by depth and study_site. The dashed line shows 0. The total number of measurements at each depth is shown at the bottom of the plot (n = 762 at 30 cm and n = 82 at 30.4 cm).

A mixed-effects model was used to analyze the effect of measurement depth while controlling for the random effect of study_site. The model showed no significant effect of depth on dSOC (Table 1).

Table 1

Random Effects		Intercept	Residual			
	study_site (StdDev)	0.18	1.04			
Fixed Effects		Value	Std Error	df	t-value	p-value
	Intercept	0.060	0.211	1956	0.283	0.777
	Depth	-0.005	0.009	14	-0.522	0.610

The validation dataset was then filtered to consider only the treatment pairs corresponding to only tillage (i.e. no consideration of tillage + cover crops or tillage + nutrient management). This analysis showed a similar trend (Figure 2) with no evidence for a negative relationship between depth of measurement and treatment-pair outcomes (Table 2).

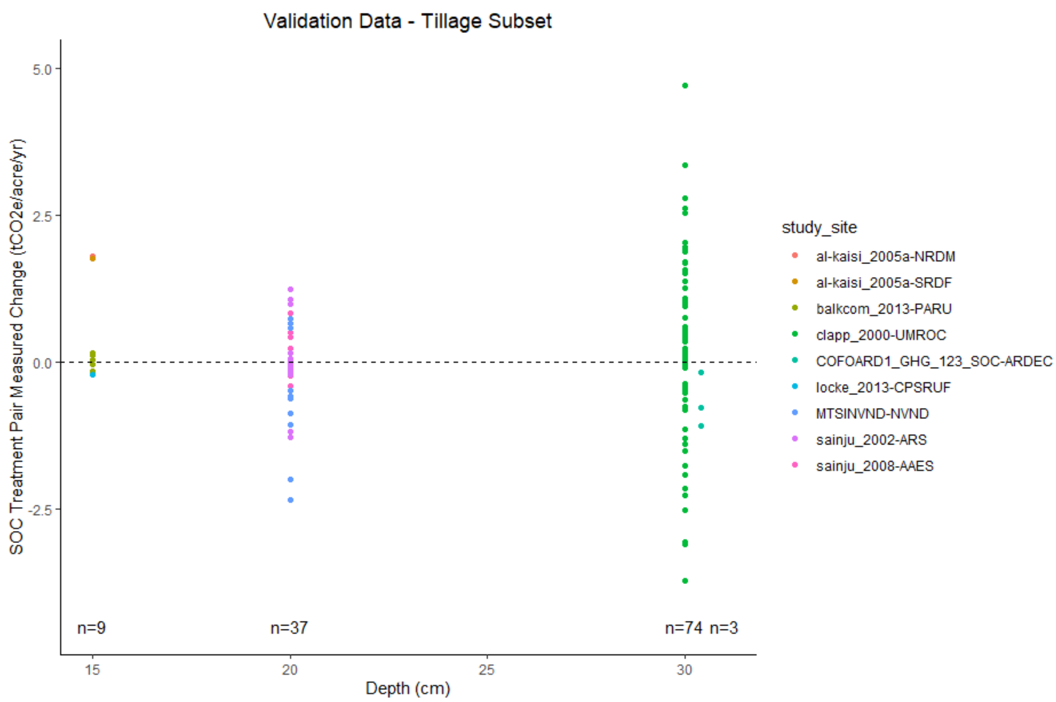

Figure 2. Measured change in SOC treatment-pairs by depth and study_site for tillage pairs only. The dashed line shows 0. The total number of measurements at each depth is shown at the bottom of the plot (n = 74 at 30 cm and n = 3 at 30.4 cm).

Table 2.

Random Effects		Intercept	Residual			
	study_site (StdDev)	0.12	1.38			
Fixed Effects		Value	Std Error	df	t-value	p-value
	Intercept	-0.404	0.648	114	-0.624	0.534
	Depth	0.021	0.025	7	0.843	0.427

Neither analysis provided evidence that Regrow's validation database overestimates treatment-paired effects on SOC changes at shallow depths. Therefore, shallow measurements remain in the database for this report.

Appendix F: Measured annual SOC changes vs duration between measurements

The temporal change in SOC is defined on an annual unit (for both measured and modeled values) in order to facilitate the required reporting of uncertainty of SOC change annually. Measurements of annual changes have higher variances for shorter durations (Figure 1). However variance due to duration is mostly stable when there are 5 or more years between measurements (Figure 2).

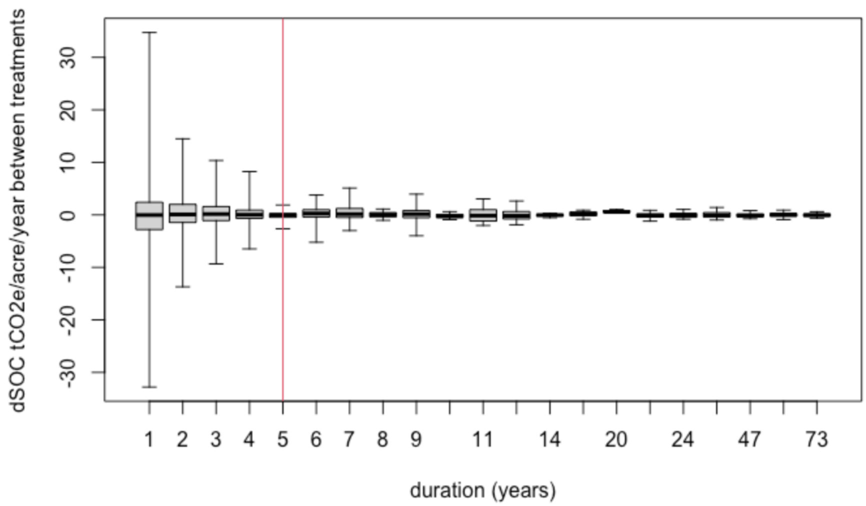

Figure 1. Annual changes of SOC in tCOe/acre/year between changes by time duration between measurements. All time durations are included.

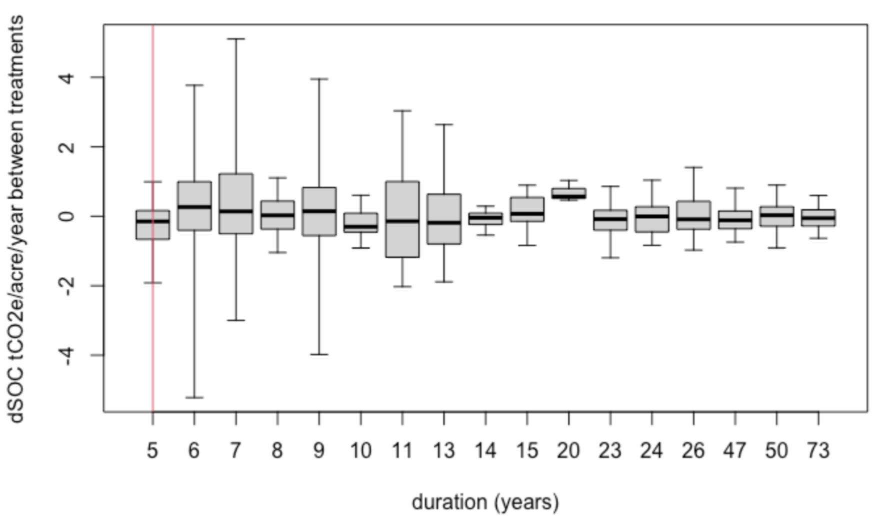

Figure 2. Annual changes of SOC in tCOe/acre/year between changes by time duration between measurements. Only time durations of 5 or more years are included.

Appendix G: Study specific bias

Table 1. Study specific bias for dSOC using equation 3.1 of Model Guidance

study	mean measured difference (tCO2e per acre per year)	mean modeled difference (tCO2e per acre per year)	bias (equation 3.1) (tCO2e per acre per year)	number of pairs
WICST	-0.6876	-0.2064	0.4812	3
MTSINVND	-0.4191	-0.1327	0.2864	630
sainju_2002	0.0743	0.2411	0.1668	198
balkcom_2013	-0.0111	0.0033	0.0144	21
sanborn_field	0.0490	0.0322	-0.0169	270
sainju_2014a	0.1617	0.1416	-0.0201	15
poffenbarger_2017	-0.1132	-0.1357	-0.0225	45
COFOARD1_GHG_123_SOC	-0.2443	-0.2740	-0.0296	82
varvel_2008	0.0687	0.0252	-0.0435	105
mitchell_2015_2017	0.0485	0.0020	-0.0466	40
locke_2013	-0.1319	-0.2896	-0.1576	10
pikul_2008	0.2074	0.0474	-0.1600	36
clapp_2000	0.0443	-0.2514	-0.2957	449
sainju_2008	-0.2213	-0.6472	-0.4259	66
al-kaisi_2005a	1.7788	0.4382	-1.3405	2

Table 2. Study specific bias for N2O using equation 3.1 of Model Guidance

study	mean measured difference (tCO2e per acre per year)	mean modeled difference (tCO2e per acre per year)	bias (equation 3.1) (tCO2e per acre per year)	number of pairs
nash_2015	-0.8576	-0.0600	0.7975	12
hernandez-ramirez_2009	-0.5940	-0.0337	0.5602	20
omonode_and_vyn_2013	-0.1333	0.0000	0.1333	2
smith_2012	-0.1290	0.0001	0.1291	28
hoben_2011	0.1021	0.2020	0.0998	15
COFOARD2_GHG	-0.0405	0.0157	0.0562	132
mcgowan_2018	-0.0126	0.0215	0.0341	36
COFOARD4	0.0194	0.0486	0.0291	760
fernandez_2015	0.0116	0.0397	0.0282	18
COFOARD3_GHG	0.0451	0.0728	0.0277	240
wegner_2018	-0.0042	0.0188	0.0231	84
SDBRREAP	0.0097	0.0180	0.0083	30
MTSINVND	-0.0028	0.0006	0.0034	2520
parkin_and_kaspar_2006	0.0012	0.0035	0.0023	30
sainju_2014a	0.0004	0.0021	0.0017	60
parkin_and_hatfield_2010	0.0644	0.0000	-0.0644	2
engel_2010	0.0751	-0.0003	-0.0754	30
nash_2012	0.1425	-0.0061	-0.1486	20
KYBGGHG	0.2409	0.0795	-0.1614	1053
COFOARD1_GHG_123_SOC	0.0407	-0.1315	-0.1722	127