Review of the *ecosys* Model Version 1.0 According to the Requirements and Guidance for Model Calibration, Validation, Uncertainty, and Verification For Soil Enrichment Projects Version 1.1a

Validation Report Prepared for the Climate Action Reserve

Reviewer: Brian McConkey, PhD, Viresco Solutions, January 17, 2024

1. Summary

This Model Validation Report of *ecosys* Model Version 1.0 (hereafter referred to as the "MVR") was for Type2 or Option 2 validation, i.e., generalized validation to demonstrate overall performance of the model without specific project.

The documentation and methods all conformed to the requirements of the Requirements and Guidance for Model Calibration, Validation, Uncertainty, and Verification for Soil Enrichment Projects Version 1.1a, April 2022 (hereafter called the "Validation Guidance").

The Climate Action Reserve permitted this validation of *ecosys* V1.0 to be done across a single validation domain consisting of the full set of declared Practice Categories (PC), Major Land Resource Regions (LRR) and Crop Functional Group (CFG) for each Emission Source (ES) of SOC and N_2O. The validation requirements of the Validation Guidance were met for this single domain. The validated domain for *ecosys* V 1.0 for SOC change and N_2O emission is summarized in Tables 1 through 3. The model has been validated for coarse to fine-textured soils. The validation domain for SOC change is for soil depths of 0-30 cm to 0-60 cm.

Table 1 Crop Function Groups in the Validated Domain

Crop functional Group	**Crop name**
Annual, C4, herbaceous, non-N-fixing, non-flooded crops	Corn
Annual, C3, herbaceous, N-fixing, non-flooded crops	Soybean

Table 2. Description and domain of Practice Categories.

Practice Category	Practices included
Disturbance	Soil disturbance driven by tillage activity
Fertilizer (inorganic N)	Magnitude, form (including enhanced efficiency fertilizers), and/or timing for nitrogen fertilizer applied

Organic (amendment)	Rate, form, and depth of manure application
Cropping	Variety of crops grown, which includes the comparison of single-crop crop rotation and double-crop rotation and the effects of planting cover crops)

Table 3. LRR in validation domain

Land Resource Regions (LRRs)	**LRR code**
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
South Atlantic and Gulf Slope Cash Crops, Forest, and Livestock Region	P

Although not required for the validation the MVR included a drill-down of validation results by CFG and PC by ES. These more detailed results showed excellent ecosys performance to match the observations SOC change and N_2O emissions in the validation data. There was no evidence of structural model problems within the validation domain. Nevertheless, given the inherently limited data for the PC of Organic amendment (consisting of five validation sites – two for SOC and three for N_2O), when additional suitable validation for that PC becomes available for SOC change and, especially, for N_2O emissions (that had the poorest coherence of modeled and observed for any PC), this reviewer recommends that the model validation report should be updated with that additional data included and the validation and model prediction error reassessed.

2. Background

The MVR (*ecosys* validation report v3.2 20240110.pdf) is for the model *ecosys* Version 1.0. The model, *ecosys* is a process-based *ecosys*tem model which simulates the holistic and coupled energy, water, carbon, and nutrient cycles. In addition to simulating SOC state and fluxes, it also estimates fluxes of N_2O and CH_4 from and to the soil. The CH_4 fluxes were not validated in this MVR.

The *ecosys* model is well described in peer-reviewed scientific literature and there are several peer-reviewed publications that show *ecosys* can accurately simulate the C and N dynamics in the geography and cropping systems in the domain relevant to this MVR. Therefore, *ecosys* Version 1.0 meets the basic scientific requirements estimating SOC changes and N_2O emissions under the Validation Guidance.

Several other models have similar high-level capabilities, including the widely used DayCent and DNDC models. *Ecosys* differs from these models in important ways. A major difference is that *ecosys* from the

above models is that *ecosys* models many processes more mechanistically. For example, whereas the above two models describe processes on a daily time step, *ecosys* models carbon flows within the soil-plant-atmosphere continuum on hourly time step and those flows are coupled with modeled hourly energy and water flows within that continuum. These coupled flows over brief time period allow the *ecosys* model to be calibrated and validated with simultaneous measured fluxes of water, energy, and carbon within the day such as is measured at research sites with eddy covariance towers. Such measured fluxes have to be integrated at least over the day to validate the other two models and so the comparison with modeled and measured data less temporal resolution of model accuracy. DayCent and DNDC use first-order kinetics where the SOC losses are represented by a simple function based on the amounts of soil organic matter and the rate of SOC decomposition. *Ecosys* differs from those models by mechanistically modeling the microbial community and then using Michaelis-Menten kinetics to describe microbially controlled enzymatic reactions for the decomposition of soil organic matter. Since the C and N cycles in the soil are intrinsically linked, the more mechanistic simulation of C cycling may improve the accuracy of estimates of N_2O fluxes.

2.1 Calibration

The model parameters have been calibrated in previous work, much of which is published in highly reputable journals. Habiterre states that none of the data used for this prior calibration was used as validation data in this MVR; all the measurement SOC changes and N_2O emission used in this MVR are independent of those used for any calibration.

2.3 Documentation

Required documentation:

a) Model version was specified
b) Description of the model calibration process
c) Same parameters are used for all LRRs

There is rigorous archiving of the *ecosys* version 1.0 including all the parameters along with process scripts and data used for validation on Github. This is available upon request to future Verifier of projects using this model.

The documentation states that site input data consists of physical site information and management information for validation data. The other inputs of hourly weather data and soil data not documented for the validation sites was from publicly available sources. The method to estimate the external water depth, data which is not available at most validation sites was described. The model parameters were held constant for the validation including the 20-yr spin-up for initialization.

This documentation of input data is compliant with the Validation Guidance.

Although not the basis for the validation in the MVR, Appendix A of MVR shows that a model-data-fusion implementation of *ecosys*, called SYMFONI, that differs from the implementation used for validation in that it uses frequent observations of localized land surface conditions from remote sensing. An important stated goal of using SYMFONI approach is to improve the estimate of plant growth. With this local surface condition data to improve estimates of plant growth, Appendix A shows that the estimate of the net *ecosys*tem [carbon] exchange was a better fit with observed values compared to when the

plant productivity was modeled by *ecosys* alone. The SYMFONI approach that uses the additional local surface conditions data as a model input data for validation would be allowable under the Validation Guidance providing it met all the requirements of the Validation Guidance. The essential requirement of the Validation Guidance must be met that there is no data used for calibration of crop parameters that was used for validation data. If the local surface data is used as model input only with all model crop growth parameters held constant for validation, then the local surface conditions are simply input data if used consistently for all validation. That would be allowable under the Validation Guidance. Local model parameters for modeling crop growth at scales finer than the LRR are allowed under the Validation Guidance but the use and values of those local crop parameters must be clearly defined and documented. Although it appears the SYMFONI approach may conform to the Validation Guidance requirements, Appendix A only indicates the potential performance of the *ecosys* model using a different input data approach. A new MVR specific to the use SYMFONI would be required to assess the validation of *ecosys* using that approach. Therefore, *ecosys* is not validated for the use of the SYMFONI approach based on this MVR.

3. Validated domain

3.1 Crop Functional Groups

The domain includes only two CFG with one crop identified for each. Table 4 shows the CFG.

Table 4 Crop Function Groups in the Validated Domain

Crop functional Group	**Crop name**
Annual, C4, herbaceous, non-N-fixing, non-flooded crops	Corn
Annual, C3, herbaceous, N-fixing, non-flooded crops	Soybean

3.2 Practice Categories and Emission Sources

The practice categories were described, and the data used for validation for each practice category and the LRR included in the validation data for each practice category. Stacked practices were not included so the requirement of having at least one study with each alone was clearly met. Table 5 summarizes the validation domain of PC.

Table 5. Description and domain of Practice Categories.

Practice Category	Practices included
Disturbance	Soil disturbance driven by tillage activity
Fertilizer (inorganic N)	Magnitude, form (including enhanced efficiency fertilizers), and/or timing for nitrogen fertilizer applied
Organic (amendment)	Rate, form, and depth of manure application

Cropping	Variety of crops grown, which includes the comparison of single-crop crop rotation and double-crop rotation and the effects of planting cover crops)

3.3 Land Resource Regions and Soil Texture

Owing to the unavailability of suitable validation data, Habiterre requested as deviation that a validation could be over a single validation regime (all PC and CFG) for each ES. CAR agreed to that deviation (Appendix F of the MVR). CAR also noted that transparency regarding the model validation relative to CFG and PC over the LRR is an important goal of the validation.

The validation domain includes eight LRR (Table 6).

Table 6. Validation domain in LRRs

Land Resource Regions (LRRs)	**LRR code**
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
South Atlantic and Gulf Slope Cash Crops, Forest, and Livestock Region	P

As a single validation regime, the validation fully met the requirement for at least 3 LRR and a range of at least 15% in clay for each ES. In fact, the validation data proved excellent coverage of the geographical domain with all LRR having validation data for SOC and seven of the eight LRR having data for N_2O. In addition, for both SOC and N_2O, several LRR contained more than one validation site.

The soil texture ranged from coarse to fine textured for validation for SOC while being coarse to medium textured for N_2O.

The PC of Disturbance, Fertilizer, and Cropping had validation data for both CFG and both ES over a range of geographical locations covering at least three LRR (some with several studies in an LRR). For the PC of Organic, there were two validation studies for SOC and three validation studies for N_2O. This reviewer strongly recommends that two validation studies are a practical minimum to demonstrate the model can effectively simulate for a PC for more than one geophysical setting. The studies used to validate SOC for this PC were different than those used for N_2O, so this PC was validated over the range of geophysical conditions found at these five separate locations. While only the crop of corn was included in the validation studies for Organic, section 3.3.1 of the Validation Guidance specifically accepts validation for this PC across annual crops without necessarily having validation data for each annual crop in the domain. Given the fact that there are an extremely limited number of suitable validation studies for this PC of Organic amendment, this reviewer considers the number of validation studies used for this validation adequate.

3.4 Validation Data

All the validation data is stated as peer-reviewed so meets the SEP Validation Guidance requirements.

The necessary site data for the validation was provided in Appendix D of the MVR. The number of observations for each study-site, the treatments , and soil texture was provided.

The distribution of time periods for SOC change was shown (Appendix E, Figure E2 of the MVR). The experimental time period for each validation site was not documented as indicated in the Validation Guidance, but these would not affect the validation for SOC as invariably it is a multiyear period, so this reviewer sees no strong rationale for documenting each time period for SOC. There is no restriction in the Validation Guidance regarding the length of time period for SOC change observations. The validation was for a mean of 13 years that would be longer than the project crediting period.

Appendix D, Table D2, of the MVR provides the time period for studies involving N_2O. The measurement duration covers at least 4 months and many cover longer time period up to full year. This reviewer is satisfied that the number of studies with sufficiently long N_2O measurements is adequate to validate *ecosys* for the entire year and, thus, for entire crediting period.

The types of measurement techniques (dry combustion for SOC and soil chambers for N_2O) for validation were included. These measurement techniques as *de facto* standards are fully acceptable.

The measurement depths used for validation varied from 15 to 75 cm across study-sites. Appendix E shows that the magnitude and variation of SOC change was not clearly affected by measurement depth. There was no indication that SOC change for study-sites having measurement depths 15 cm were different from a measurement depth of 30 cm or deeper than 30 cm. Therefore, this reviewer is satisfied that the selection of data with their varied depths was acceptable for the validation over this domain. Since the majority (62%) of study sites had depths of 60 cm or deeper, the *ecosys* model has been validated for a total soil depth from the Soil Enrichment Protocol minimum of 0-30 cm to depth of up to 0-60 cm (a project based on this validation would need to specify the soil depth for SOC quantification).

4. Assessment of Bias, Model Prediction Error, and Goodness of Fit

Section 9 of the MVR adequately describes the procedures used to derive the pooled measurement uncertainty (PMU). The report provides example derivations of PMU as required by the Validation Guidance. A single PMU was provided for each ES consistent with the CAR ruling that validation can be across the whole domain.

The method to estimate the model prediction error for each ES is based on the error of model versus measured values for the difference in emission between with- and without practice change. This would be the difference in change of SOC between with and without practice change for ES of SOC and the difference in N_2O fluxes between with and without practice change for the ES of N_2O.

Over the single domain, the *ecosys* model effectively met the bias requirement that the mean bias is less than the PMU for each ES. The biases by study were listed and there were only a few studies at each end of the distribution of biases for which the absolute value of the bias exceeded the PMU. Thus, there was no indication of any tendency to have larger positive or negative biases. The required histograms of

residuals between measured and modeled showed an approximate symmetrical distribution of residuals around near-zero mean. Over 90% of measured values for each ES fell within the 90% prediction intervals. Hence, the *ecosys* model fully met the validation requirements for the permitted single domain.

Although not required for that permitted validation for the single domain, drilling down into the individual PC and CFG is recommended to provide greater transparency regarding *ecosys* performance across the validation domain (these results within the validation domain are contained is Section 9, see Table 9, and Appendix G of the MVR). For each PC and each CFG, the mean bias for SOC was less than relevant PMU. This was also true for N_2O with the exception of the PC of organic for which the bias was larger than the PMU. For each PC and CFG, for both ES, the agreement between modeled and measured differences in SOC and N_2O was good with more than 90% of the measured values consistently within the 90% model prediction interval with the exception, again, of N_2O for the PC of Organic amendment.

The bias was tabulated in the drill down for each site by PC and CFG. The histograms of modeled minus observed for all observation pairs were presented in Appendix G by PC and CFS. Both the site biases and observation displayed a symmetrical distribution around a near-zero mean. There was no apparent evidence that there was a pattern to deviations between modeled and measured difference in SOC change across the range of measured values. For N_2O, there was evidence that N_2O emissions were overestimated for lower observed N_2O emission differences and underestimated for higher observed N_2O emission differences. This tendency is most obvious across the whole domain (Figure 9) but also sometimes apparent for individual PC and CFG domains (e.g. Fertilizer, Figure G17, Appendix G). This tendency does not suggest a structural model issue as it is expected since modeling is an averaging process across a range of conditions while observed emissions are notoriously variable temporally due to particular conditions that occur at some times. Therefore, the tendency reflects *ecosys* estimating differences closer to the average and not predicting as accurately the highest and lowest observed emission across the individual studies. Good model performance for estimating N_2O emissions in a project with many fields requires the average N_2O emission be simulated well so this reviewer has no concerns about the ability of *ecosys* to estimate project N_2O emissions.

For assessing bias, the PMU is conservative. The 90% confidence interval of measurement uncertainty would be about 2 times the pooled PMU (assuming 60 degrees of freedom in the calculation of the PMU). Although a bias falling within the confidence limits of the measurement uncertainty is not a criteria for acceptance under the Validation Guidance, it provides a way to distinguish a mean bias that is larger than the PMU but which could be reasonably expected given the confidence limits from a bias that is more concerning because they lie outside those confidence limits. For N_2O emissions for the PC of Organic amendment, the mean bias (0.24) is within the 90% confidence limits (±0.26) of the PMU. Therefore, the observed bias for the small sample of seven observation pairs is not an alarming indication that the model has fundamental problems with the estimation of N_2O emission for that PC. Further, the distribution of modeled versus measured N_2O emissions (Figure G19) and the differences between modeled and measured emissions (Figure G20), do not show indications of structural problems with the model, such as would be indicated by strong model tendency to more consistently either over- or underestimate those emissions.

In conclusion, the validation for all PCs were fully met by the validation assessment across the whole domain as approved by the Climate Action Reserve. The supplemental drill down by PC or CFG for both ES did not give this reviewer any concern about the ability of *ecosys* to model SOC change and N_2O emissions within the domain. The comparison between observed and modeled N_2O emission differences for the PC of Organic amendment showed the weakest model performance. However, given model performance over the limited amount of data for validation of this PC, this reviewer accepts that the *ecosys* model has demonstrated acceptable simulation of N_2O emissions for the PC of Organic amendment. Nevertheless, given the inherently limited data for the PC of Organic amendment, when additional suitable validation for that PC comes available for SOC change and, especially, for N_2O emissions, it is recommended the model validation report be updated to include that additional new validation data and the validation model prediction error be reassessed.

Annex. Review Requests and Habiterre Responses during validation Report Review Process

Item No.	Type of feedback (Nonconformance; Request for Clarification; Opportunity for Improvement)	Description of item	Outcome
1	Clarification	Attestation that no data used for validation was every used for calibration	Resolved.
2	Clarification	Show that SOC change for soil depths less than 30 cm are not fundamentally different than those for 30 cm or deeper.	Resolved, Appendix E
3	Clarification/Nonconformance	Show that the majority of depths for SOC were 30 cm or more	Resolved.
4	Nonconformance	Specify the degree of stacking used and attest that at least one validation study for each PC had no stacking.	Resolved.
5	Clarification	Specify what particular practice types are included in the practice categories.	Resolved.
6	Nonconformance	Soil texture classes should be consistent with standard	Resolved.

Item No.	Type of feedback (Nonconformance; Request for Clarification; Opportunity for Improvement)	Description of item	Outcome
		USDA classes	
7	Clarification	More clarity on the documentation of calculation of the method for calculating the standard error.	Resolved.
8	Nonconformance	Specify the IPCC climate zones for each validation site.	Resolved.
9	Clarification	Specify the duration of N_2O flux measurement to document that many studies included the non growing season and some were for the entire year.	Resolved. There was good coverage of non-growing season fluxes in the validation data set.
10	Nonconformance	Include the number of points within and outside the 90% prediction interval.	Resolved.
11	Clarification	Document the GWP to convert N_2O to CO2e.	Resolved.
12	Nonconformance	Insufficient LRR for the CGFxPCxES bins.	Resolved. Variance from CAR received to do validation across the entire domain (Appendix F)
13	Clarification	Specify the data sources used for model input data if not provided specifically by the validation study.	Resolved.
14	Clarification	Provide description how the important external water table input data was depth was estimated since that data is rarely available with validation site documentation.	Resolved.

Item No.	Type of feedback (Nonconformance; Request for Clarification; Opportunity for Improvement)	Description of item	Outcome
15	Clarification	Document the model initialization procedure.	Resolved.
16	Clarification	Correct the units for MSE.	Resolved.
17	Improvement	This reviewer strongly recommends at least two studies for each PC for each ES. The Organic amendment PC had only one validation study for both SOC and N_2O	Resolved. Organic amendment has two studies for both SOC and N_2O
18	Improvement	This reviewer strongly recommends that there be at least one validation study within each LRR in the validation domain.	Resolved. Studies added so that each LRR has at least one study. Each LRR has a validation study for SOC and all but one LRR have a N2O validation study.
19	Improvement	Some histograms of modeled – observed differences did not have the means shown and there were no histograms for the Organic amendment in the drill down analysis by PC and CFG (Appendix G).	Resolved, histograms were corrected and the Organic amendment fit and histograms are now included
20	Clarification	Be more specific about situation of bias and PMU in Table 9.	Resolved.