Session 3.2
Approaches for estimating soil organic carbon

Elisa Bruni and Bertrand Guenet

Ecole Normale Supérieure – Laboratoire de Géologie, Paris

UNFCCC Webinair

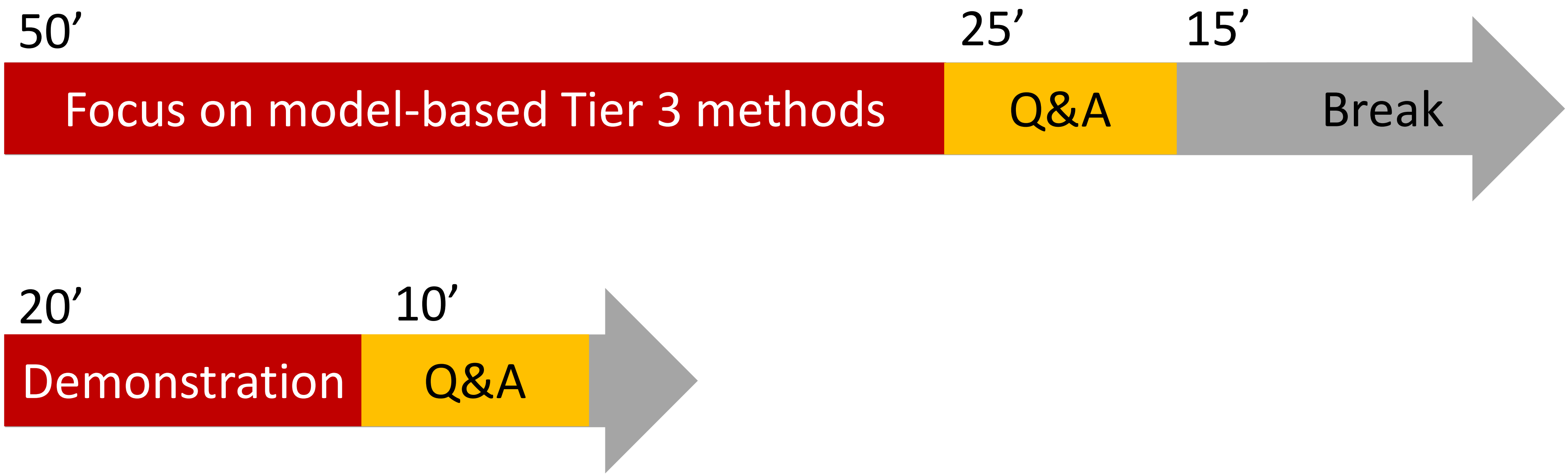
Agenda

50’ Focus on model-based Tier 3 methods

25’ Q&A

15’ Break

Agenda


50’
Focus on model-based Tier 3 methods
25’
Q&A
15’
Break
20’
Demonstration
10’
Q&A

Learning objectives

- **Data need** for model-based Tier 3 methods
- Understand **advantages and limitations**
- See examples of **inventory report with Tier 3**

Focus on model-based Tier 3 methods | Q&A | Break

1. Soil organic carbon models
2. Advantages and limitations
3. Steps of modeling
4. Case study

1. Soil organic carbon models
2. Advantages and limitations
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Annual carbon stock changes in AFOLU

$$\Delta C_{AFOLU} = \Delta C_{FL} + \Delta C_{CL} + \Delta C_{GL} + \Delta C_{WL} + \Delta C_{SL} + \Delta C_{OL}$$

- AFOLU = Agriculture, Forestry and Other Land Use
- FL = Forest Land, CL= Cropland, GL = Grassland, WL=Wetlands, SL= Settlements, OL = Other Land

Eq 2.1 IPCC Guidelines 2006

For a given land-use category

$$\Delta C_{LU} = \Delta C_{AB} + \Delta C_{BB} + \Delta C_{DW} + \Delta C_{LI} + \Delta C_{SO} + \Delta C_{HWP}$$

- AB = above-ground biomass
- BB = below-ground biomass
- DW = deadwood
- LI= litter
- SO = soils
- HWP = harvested wood products

Eq 2.3 IPCC Guidelines 2006

For a given land-use category

$$\Delta C_{LU} = \Delta C_{AB} + \Delta C_{BB} + \Delta C_{DW} + \Delta C_{LI} + \Delta C_{SO} + \Delta C_{HWP}$$

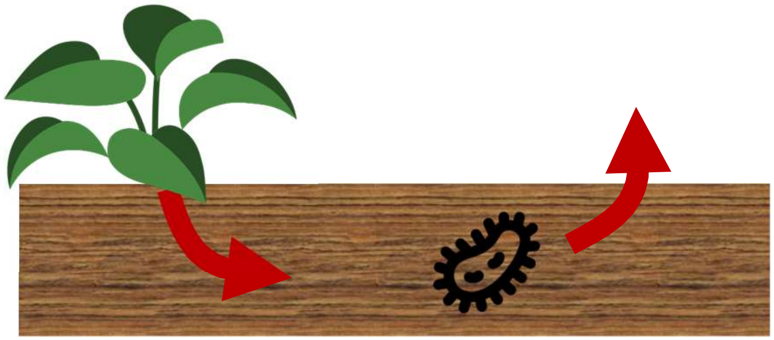
Soil organic carbon stock changes

- AB = above-ground biomass
- BB = below-ground biomass
- DW = deadwood
- LI= litter
- SO = soils
- HWP = harvested wood products

Eq 2.3 IPCC Guidelines 2006

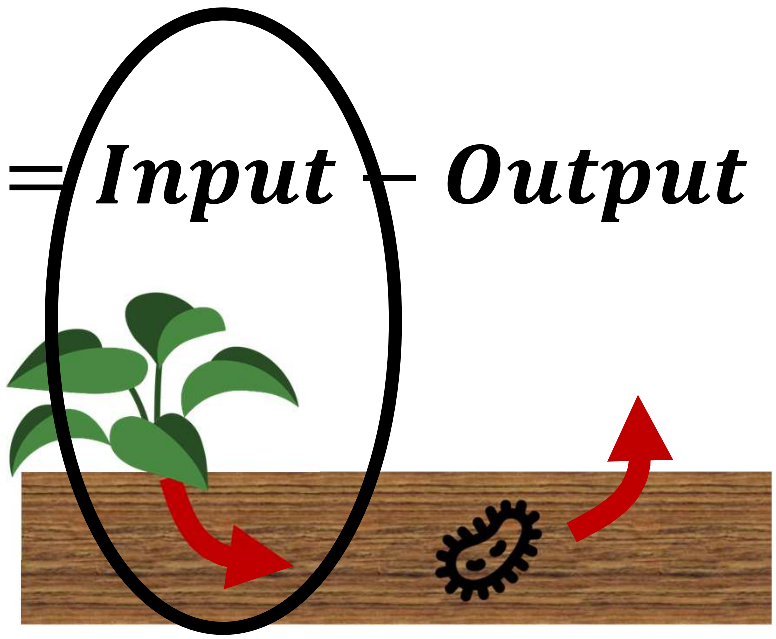
Soil organic carbon stock changes

$$\frac{\mathrm{d}\boldsymbol{C}(\mathrm{t})}{\mathrm{dt}} = \boldsymbol{Input} - \boldsymbol{Output}$$



Soil organic carbon stock changes

$$\frac{\mathrm{d}\boldsymbol{C}(\mathrm{t})}{\mathrm{dt}} = \boldsymbol{Input} - \boldsymbol{Output}$$



Soil organic carbon stock changes

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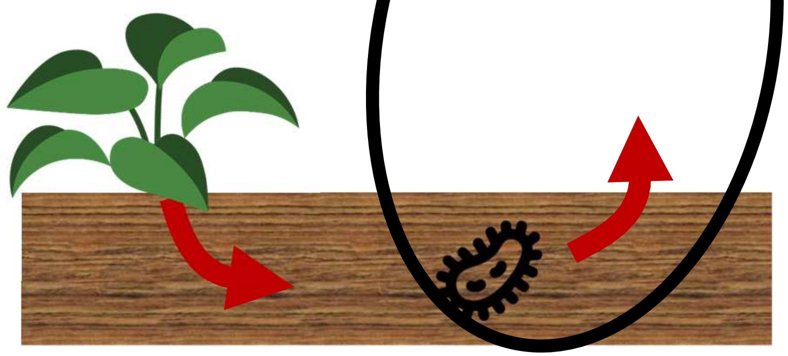
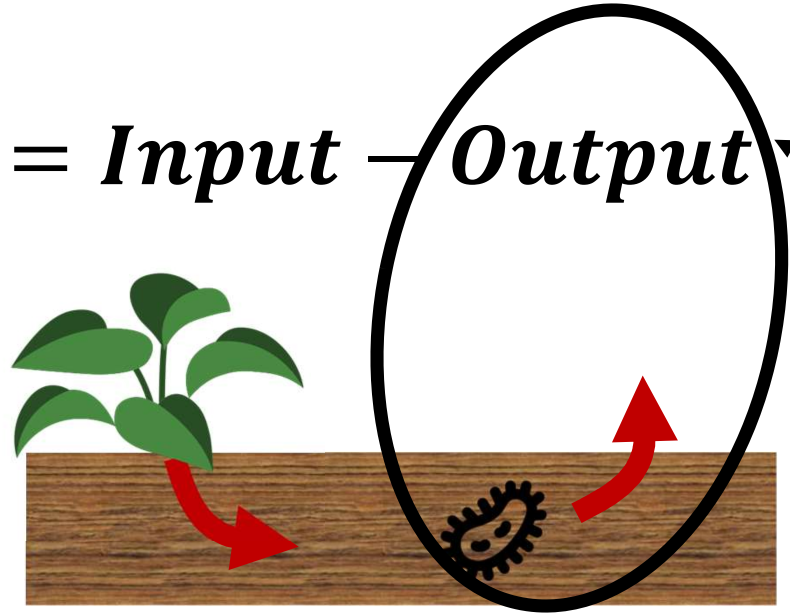
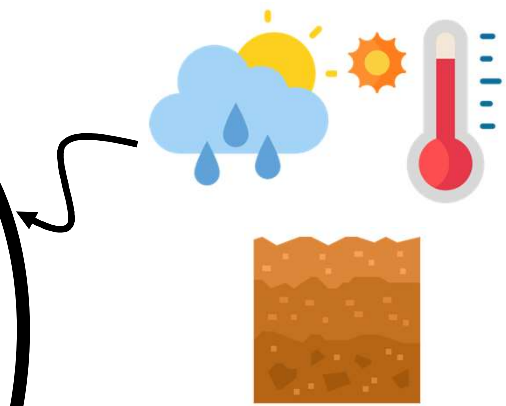


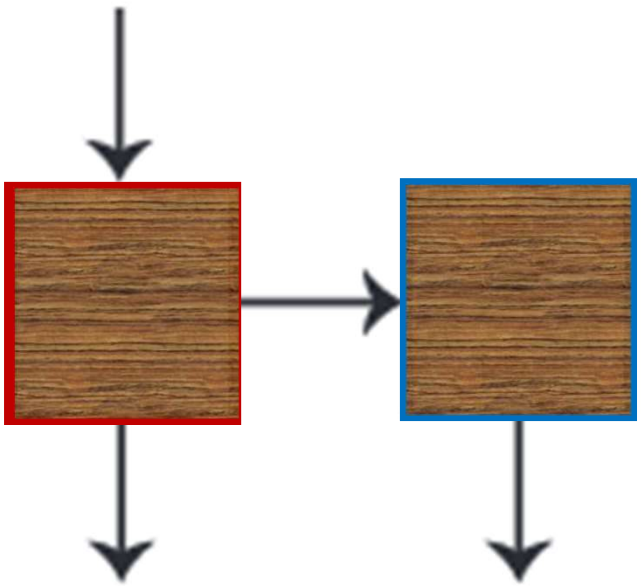
Soil organic carbon stock changes

$$\frac{\mathrm{d}C(\mathrm{t})}{\mathrm{dt}} = \boldsymbol{Input} - \boldsymbol{Output}$$

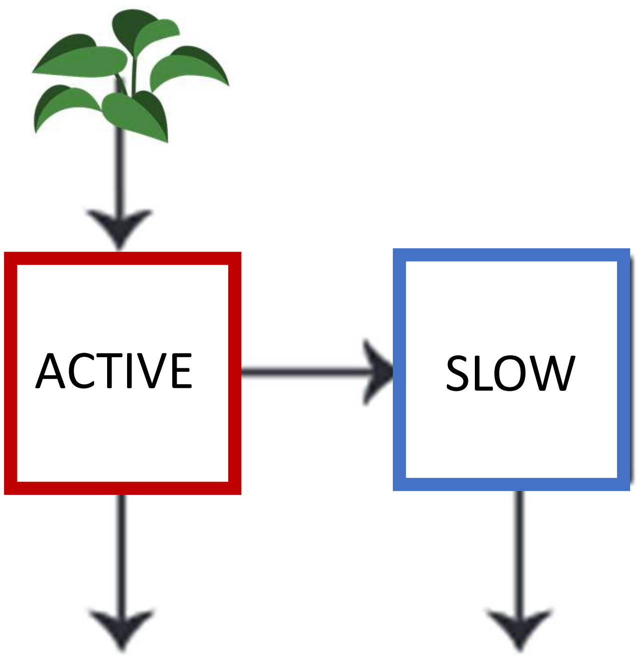




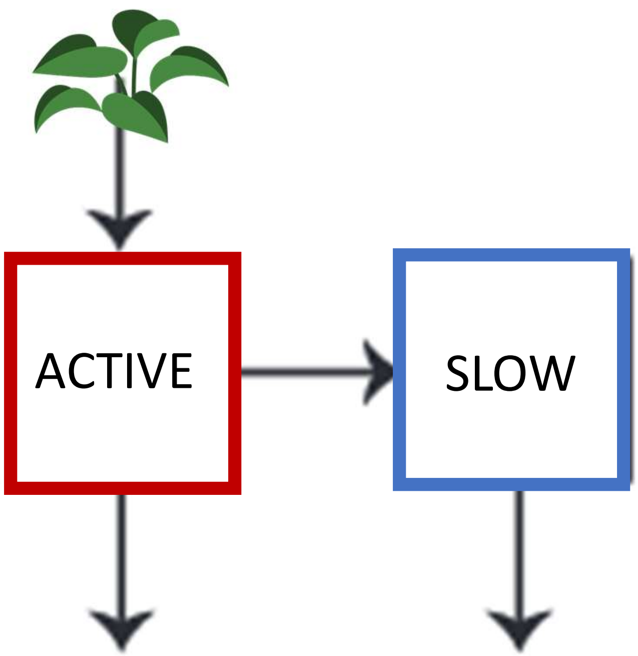
Discretization of the soil in compartments



Discretization of the soil in compartments



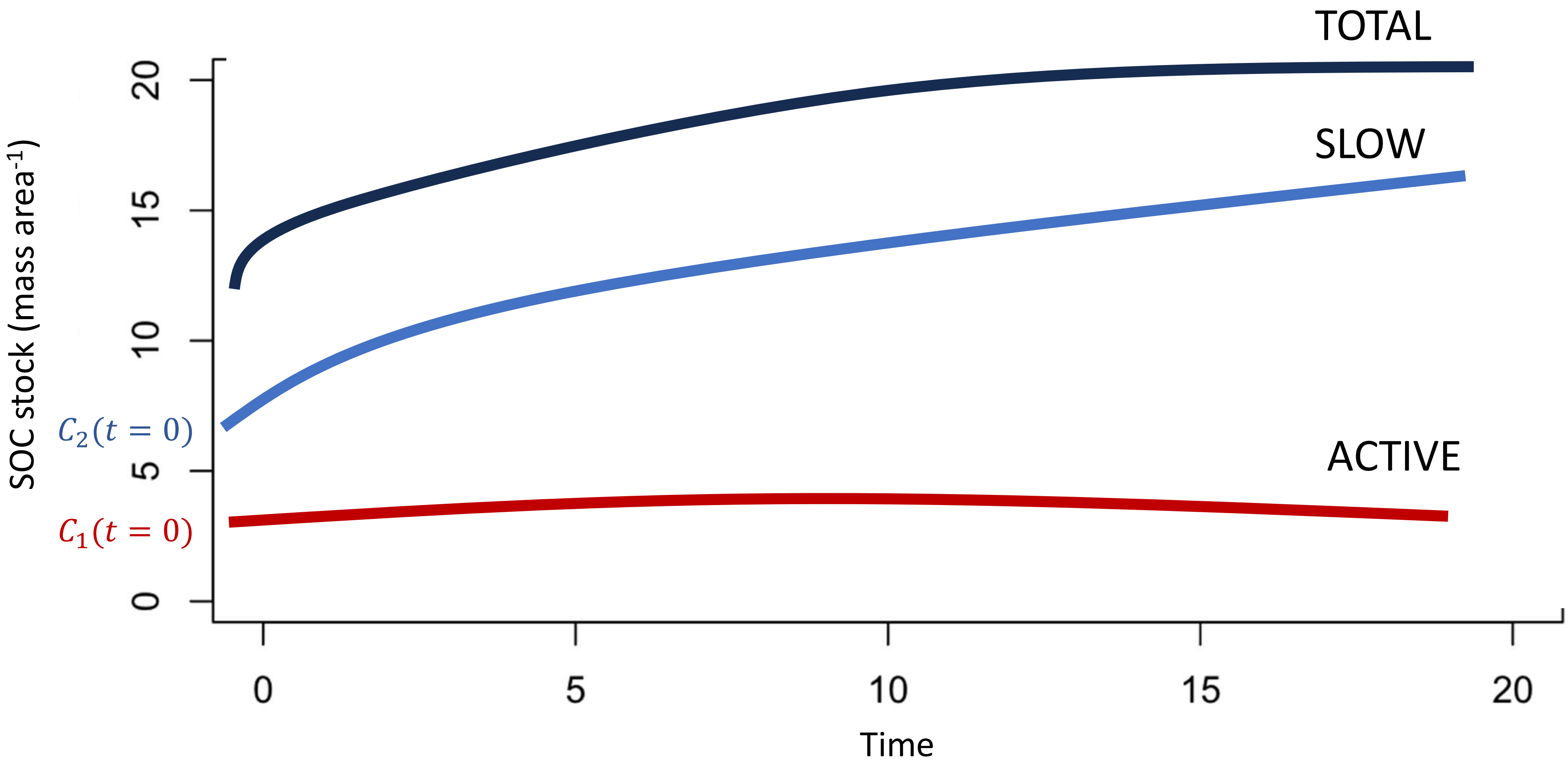
A two-pool model



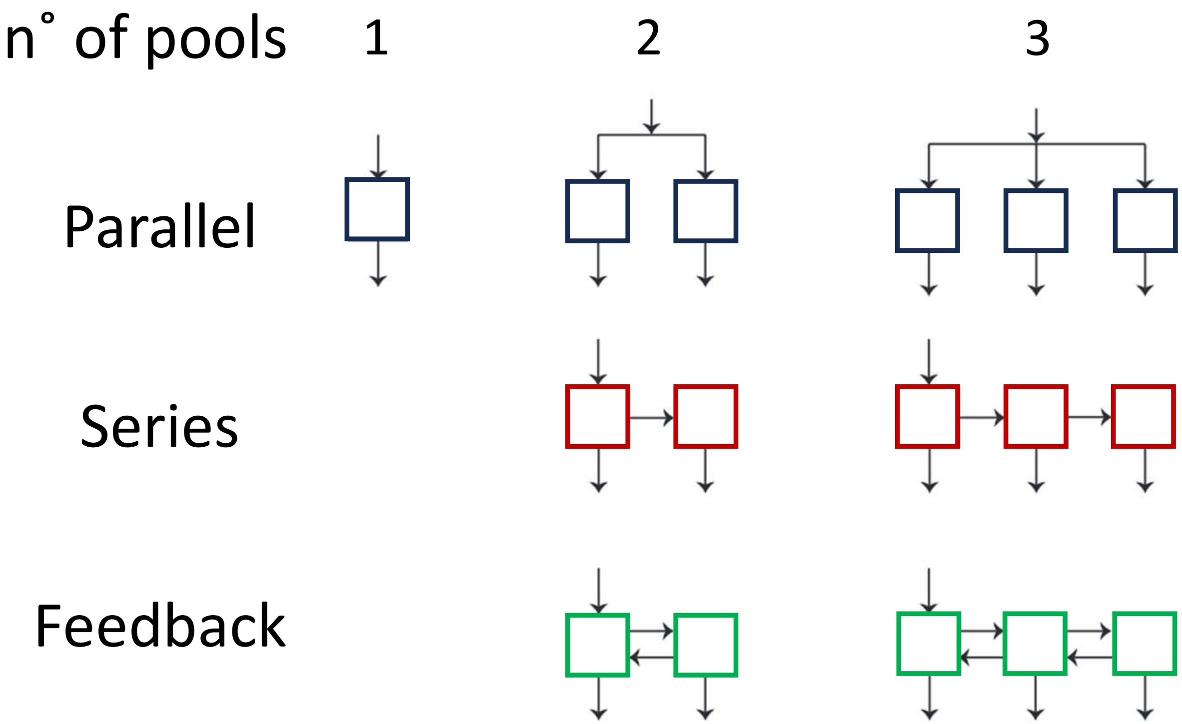
$$\frac{dC_1(t)}{dt} = Input_1 - Output_1$$

$$\frac{dC_2(t)}{dt} = Input_2 - Output_2$$

$$C_1(t = 0)$$
$$C_2(t = 0)$$

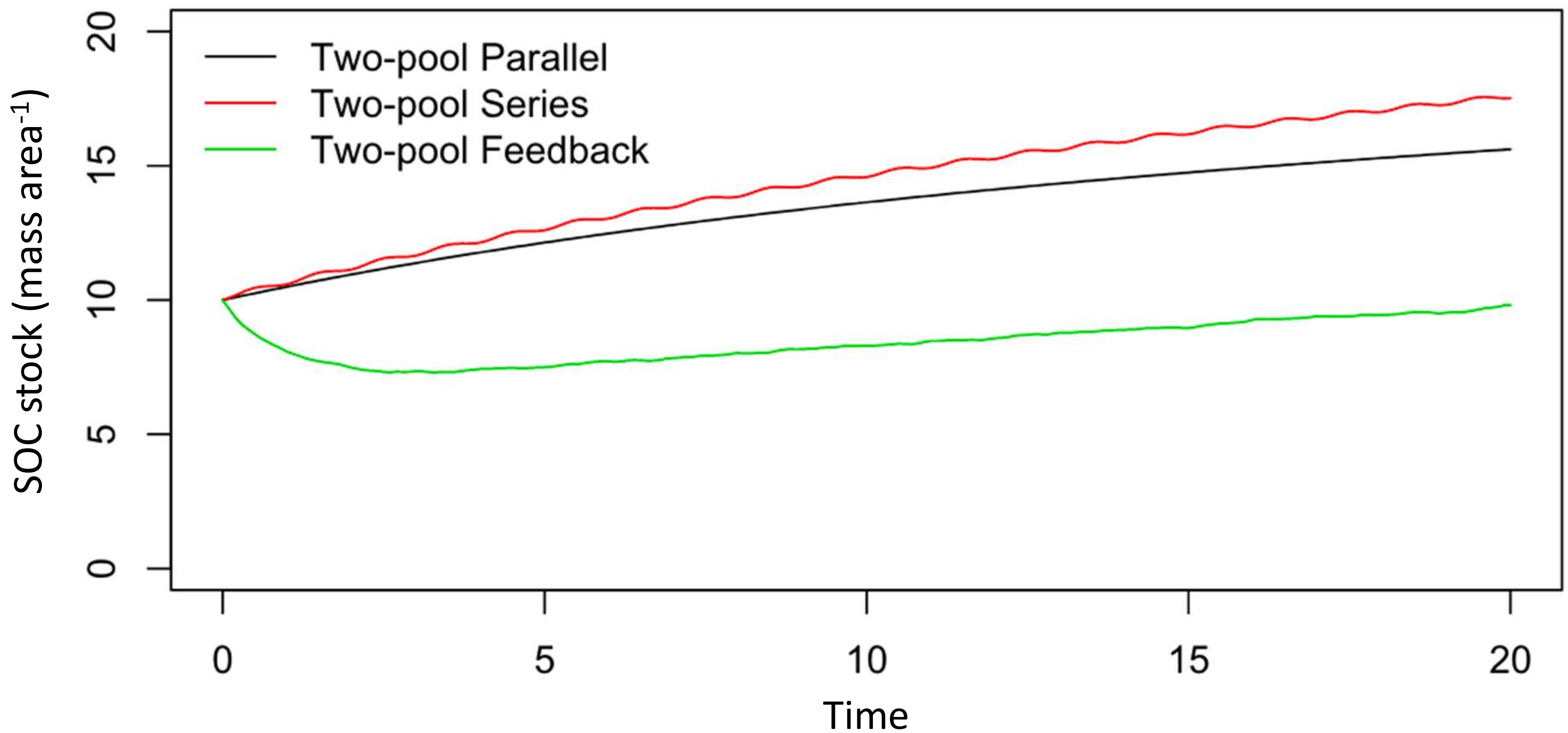

TOTAL
SLOW
ACTIVE
SOC stock (mass area-1)
$C_2(t = 0)$
$C_1(t = 0)$
0
5
10
15
20
Time

Other possible model structures



Sierra et al., 2012

Effect of the structure on the predictions

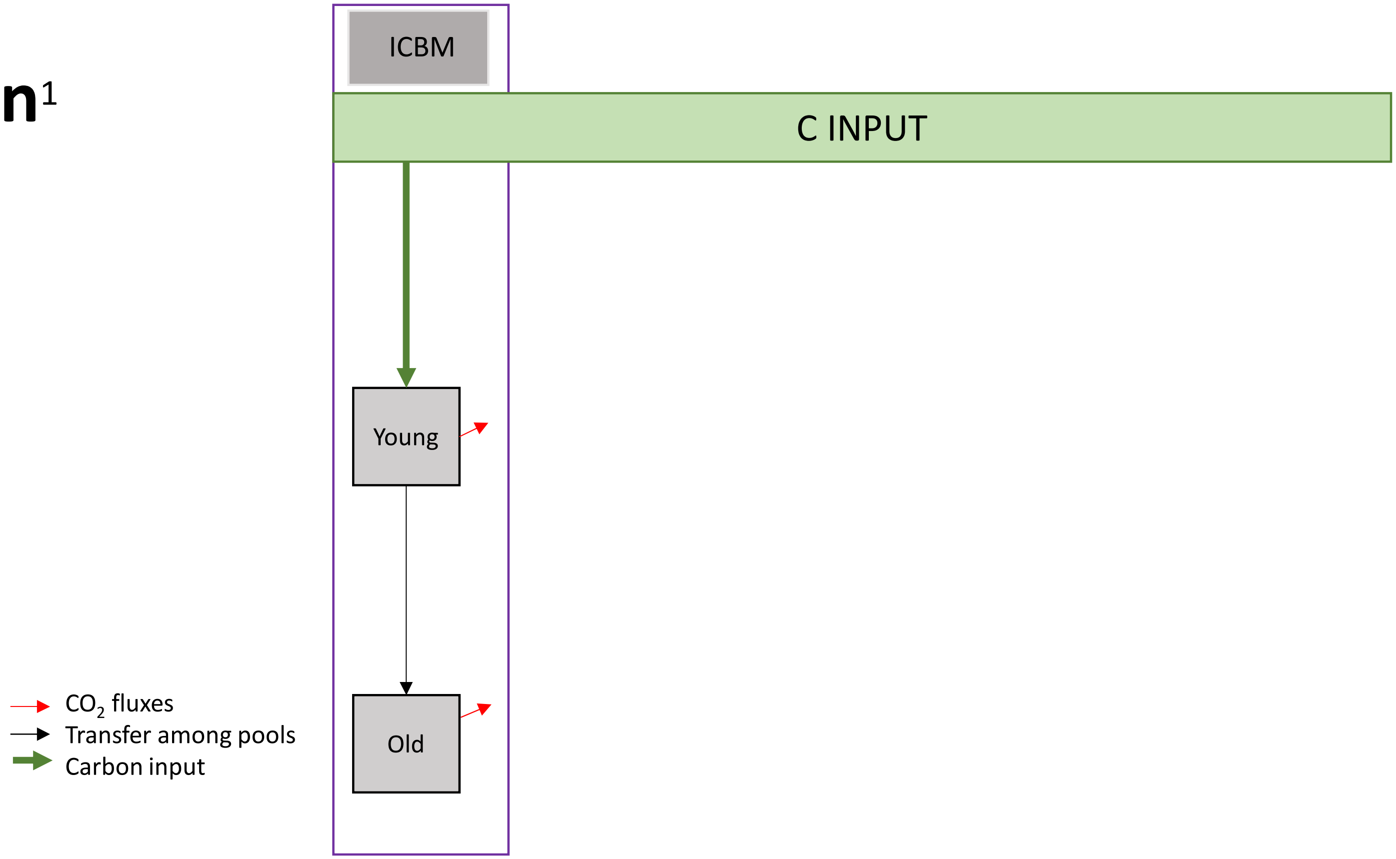


Sierra et al., 2012

Models used for national C inventories

Models used for national C inventories

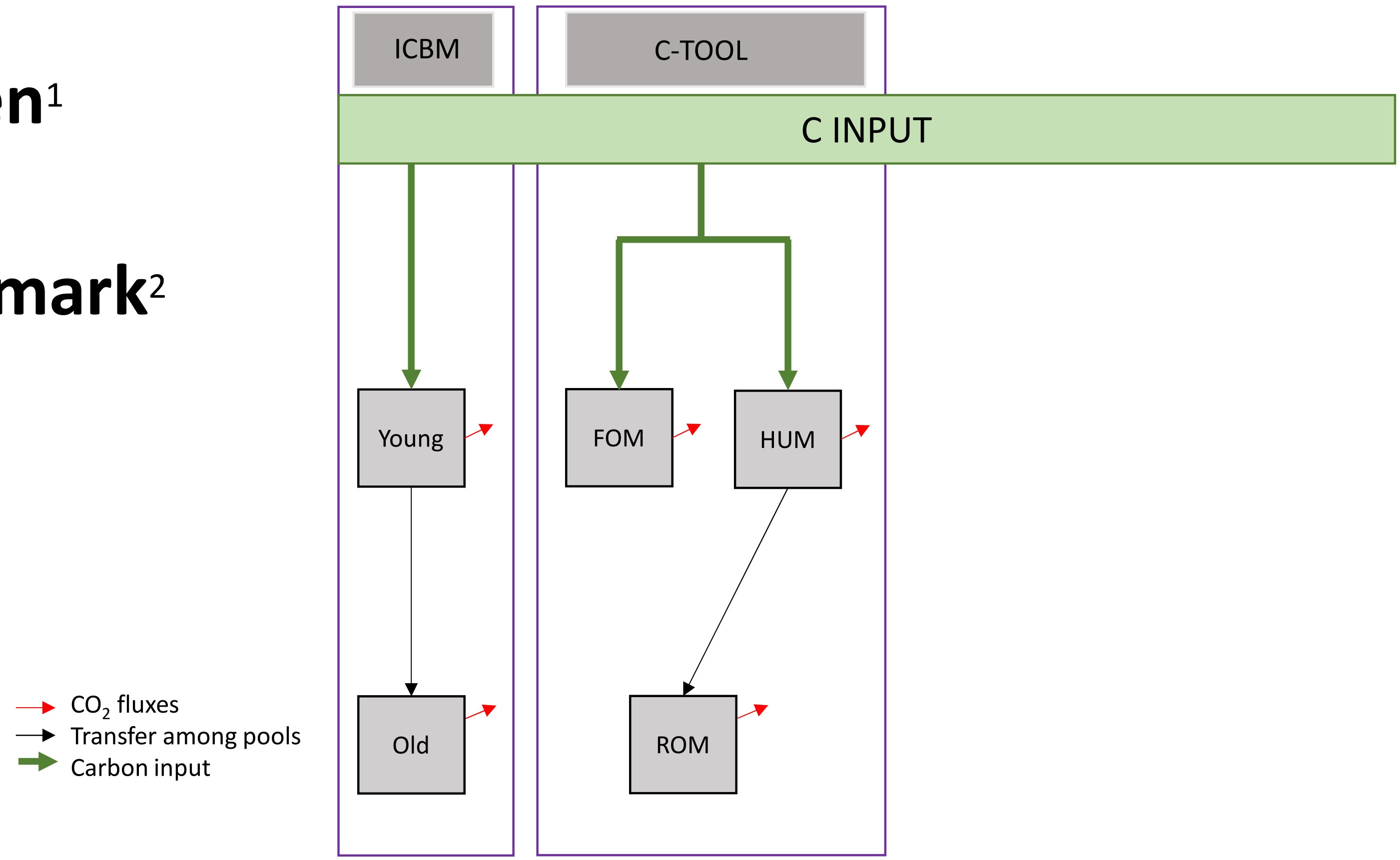
- **ICBM** in **Sweden**[1]



[1] Swedish Environmental Protection Agency, 2017

Models used for national C inventories

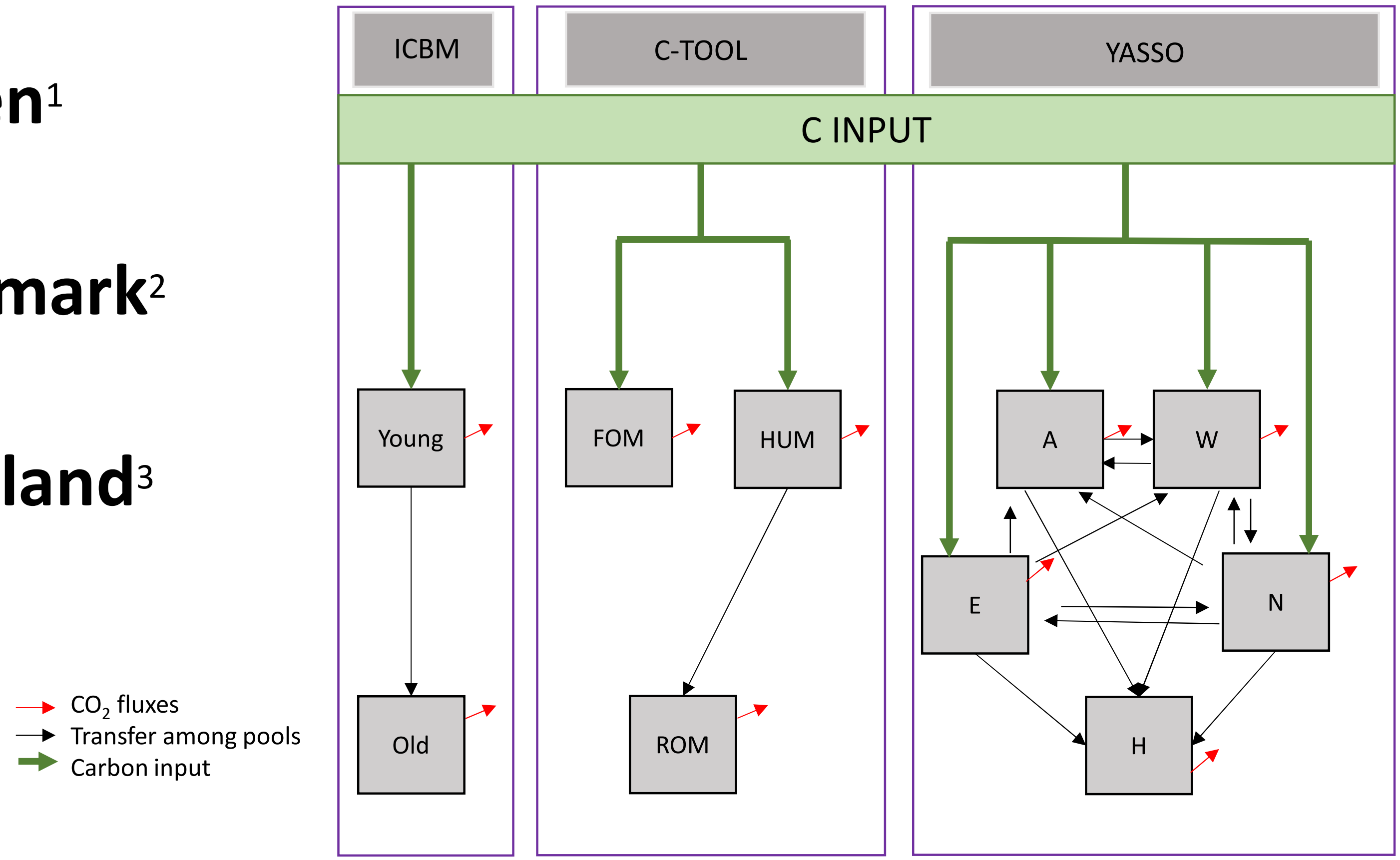
- **ICBM** in **Sweden**[1]
- **C-TOOL** in **Denmark**[2]



[1] Swedish Environmental Protection Agency, 2017; [2]Nielsen et al., 2017

Models used for national C inventories

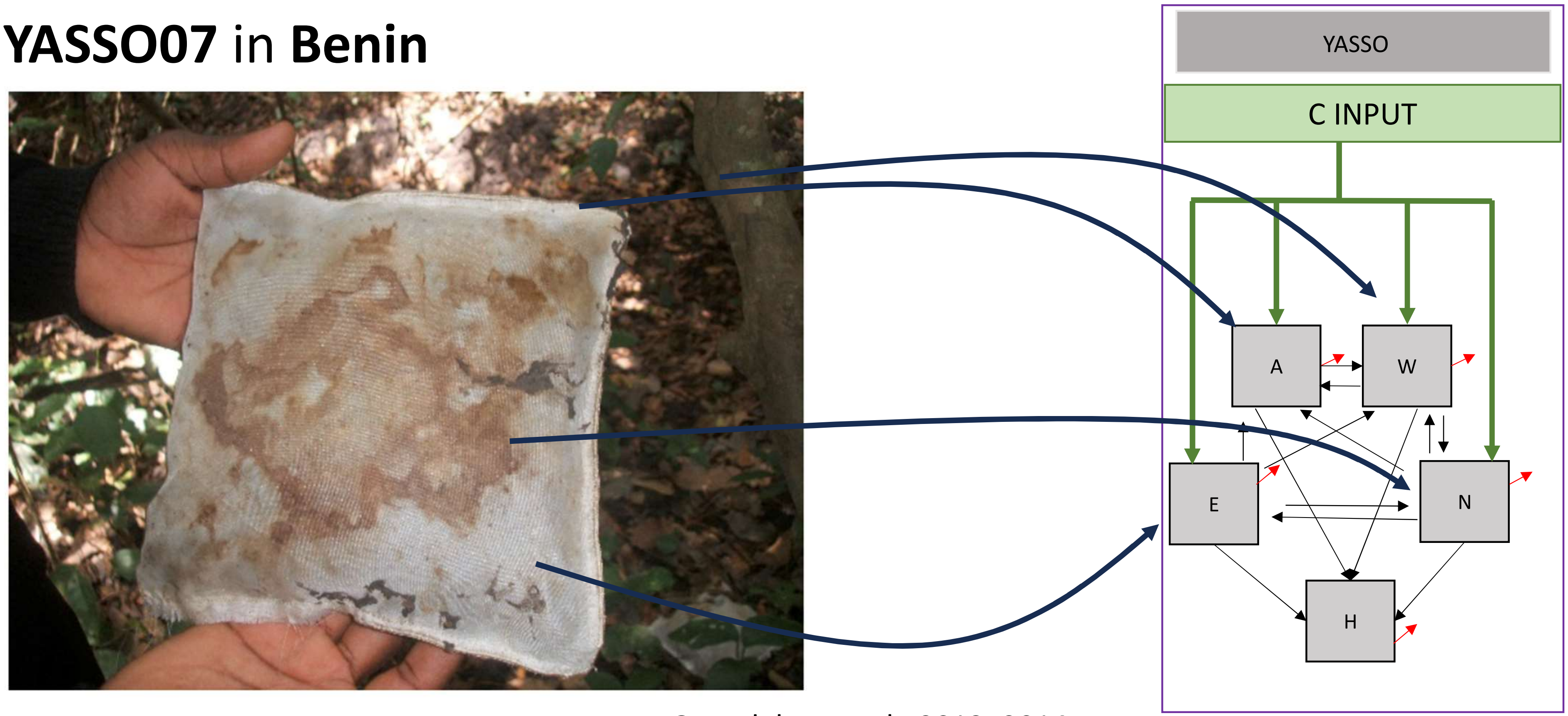
- **ICBM** in **Sweden**[1]
- **C-TOOL** in **Denmark**[2]
- **YASSO07** in **Finland**[3]



[1] Swedish Environmental Protection Agency, 2017; [2]Nielsen et al., 2017; [3]Pipatti et al., 2017

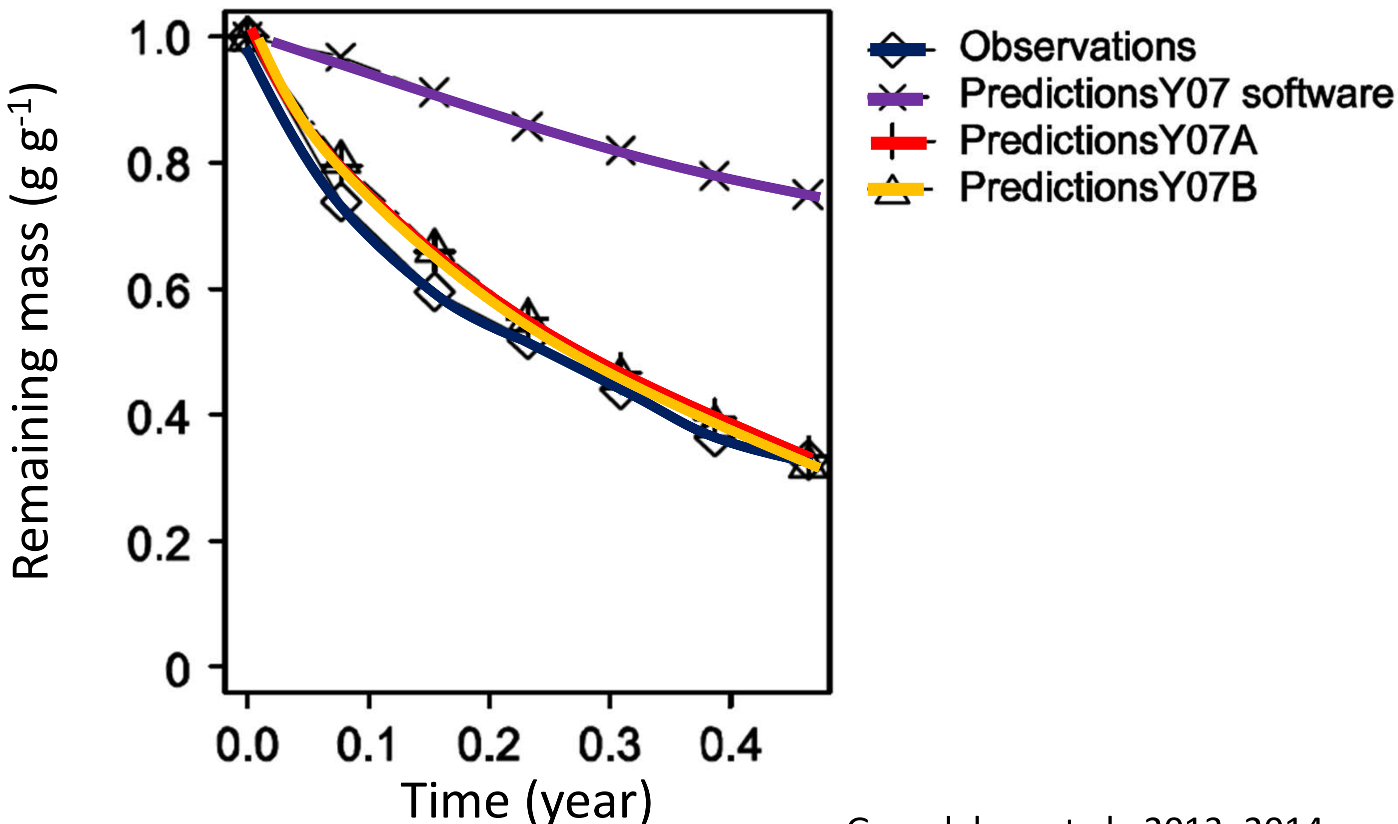
Yasso07 adapted to tropical conditions

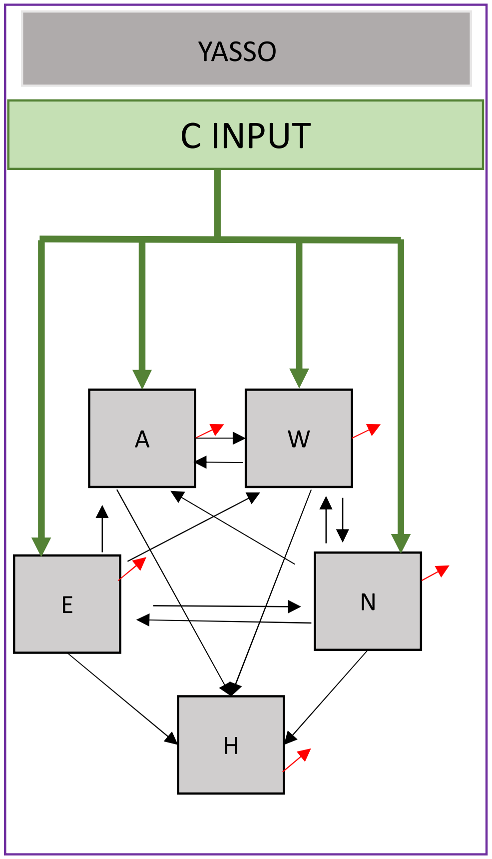
YASSO07 in **Benin**



Guendehou et al., 2013; 2014

Yasso07 adapted to tropical conditions



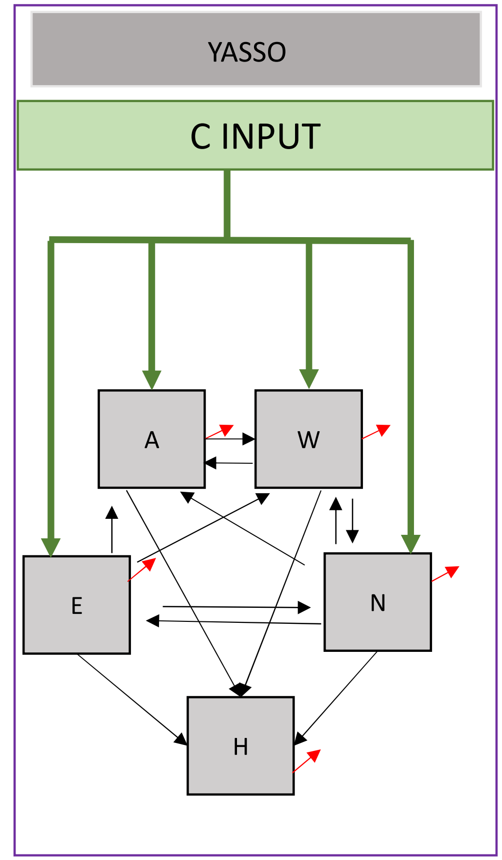


Guendehou et al., 2013; 2014

Yasso07 adapted to tropical conditions

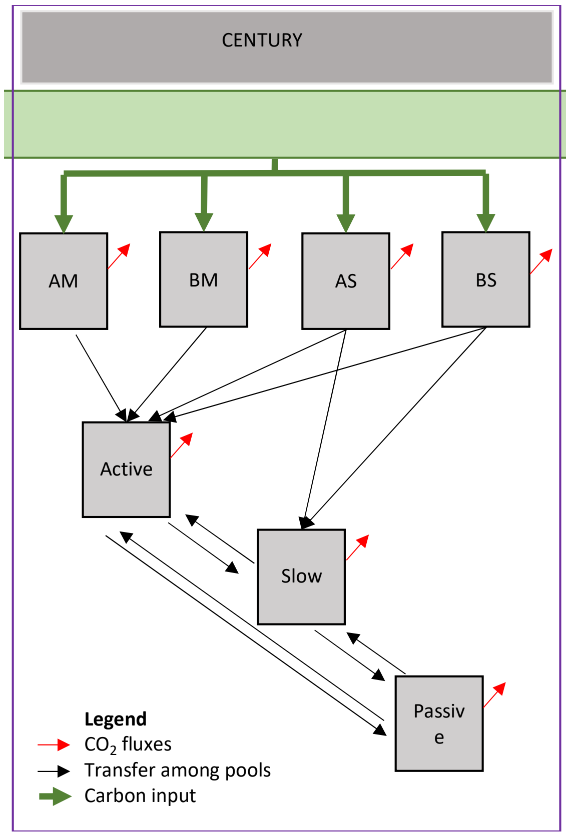
YASSO07 in **Tanzania**


FAO FORESTRY PAPER
168
Soil carbon monitoring using surveys and modelling
General description and application in the United Republic of Tanzania



Mäkipää et al., 2012 - FAO

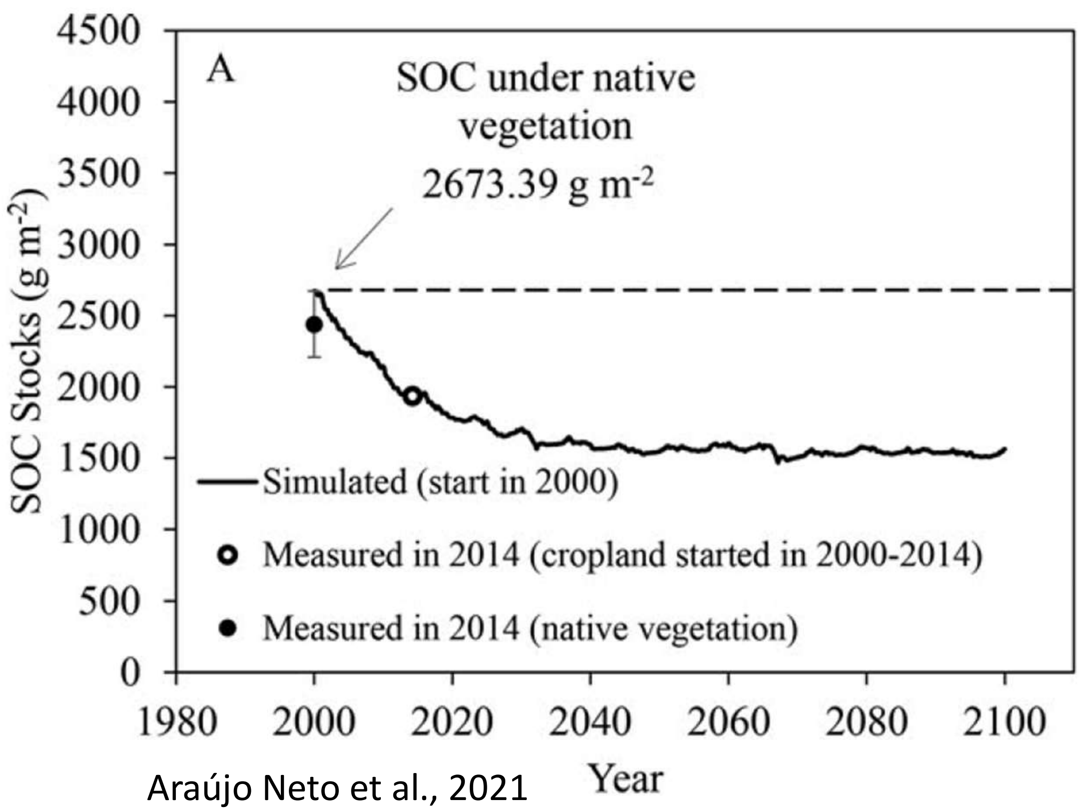
Century adapted to semi-arid conditions



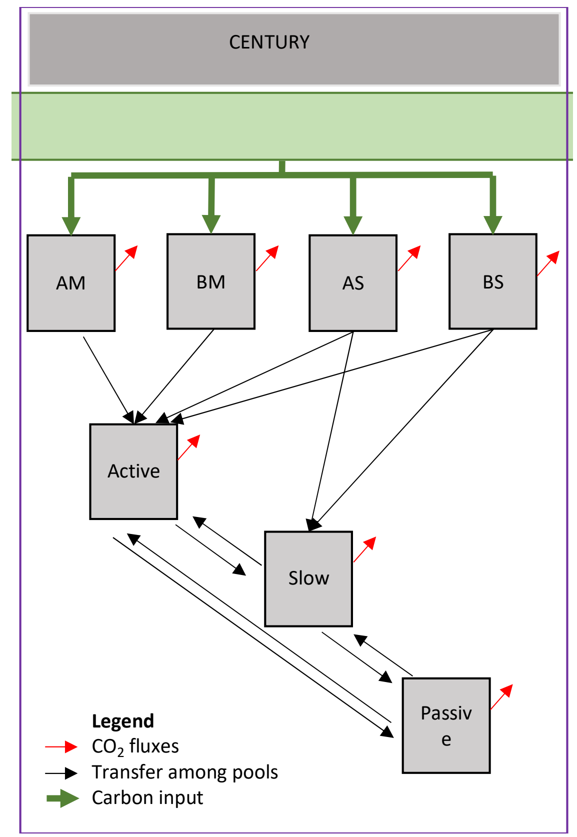
Parton et al., 1988

Century adapted to semi-arid conditions

Century in **Brazil**



Araújo Neto et al., 2021

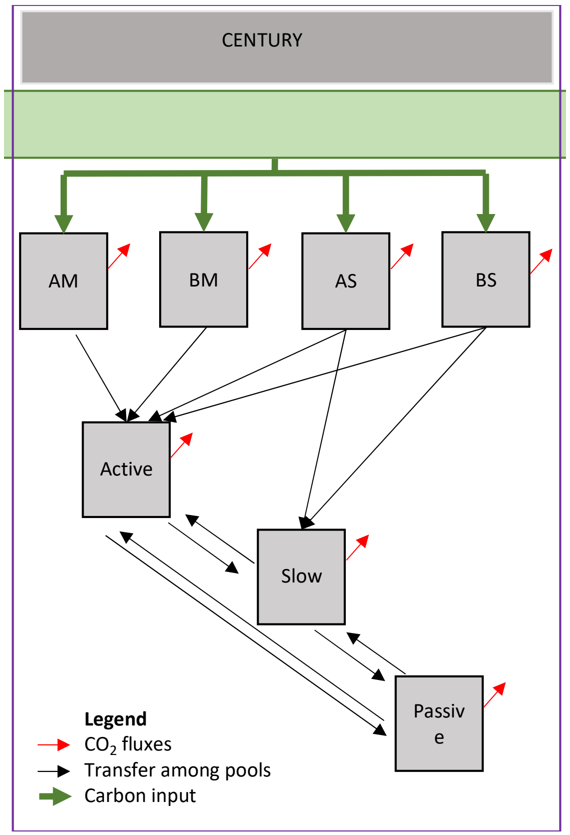


Parton et al., 1988

Century adapted to semi-arid conditions

Need of **long-term** experimental research to constrain decomposition dynamics

Araújo Neto et al., 2021



Parton et al., 1988

QUESTIONS?

1 Soil organic carbon models

2 Advantages and limitations

3 Steps of modeling

4 Case study

Tier 3 methods

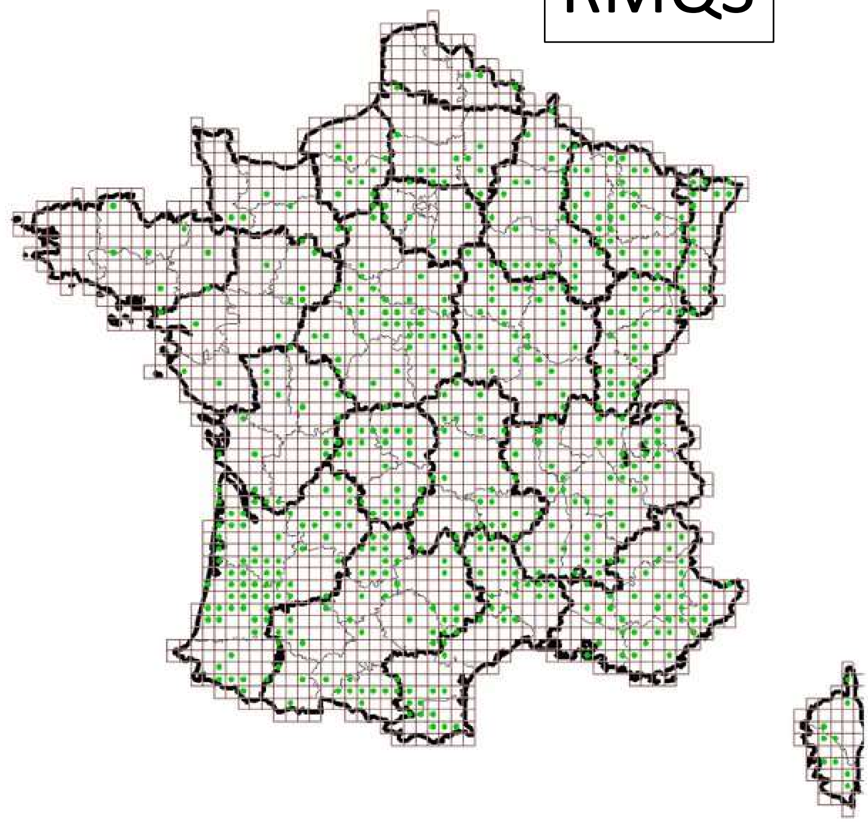
- Measurement-based
- Model-based

Tier 3 methods

- Measurement-based

Extensive measurements networks to **calculate** SOC stock changes

RMQS

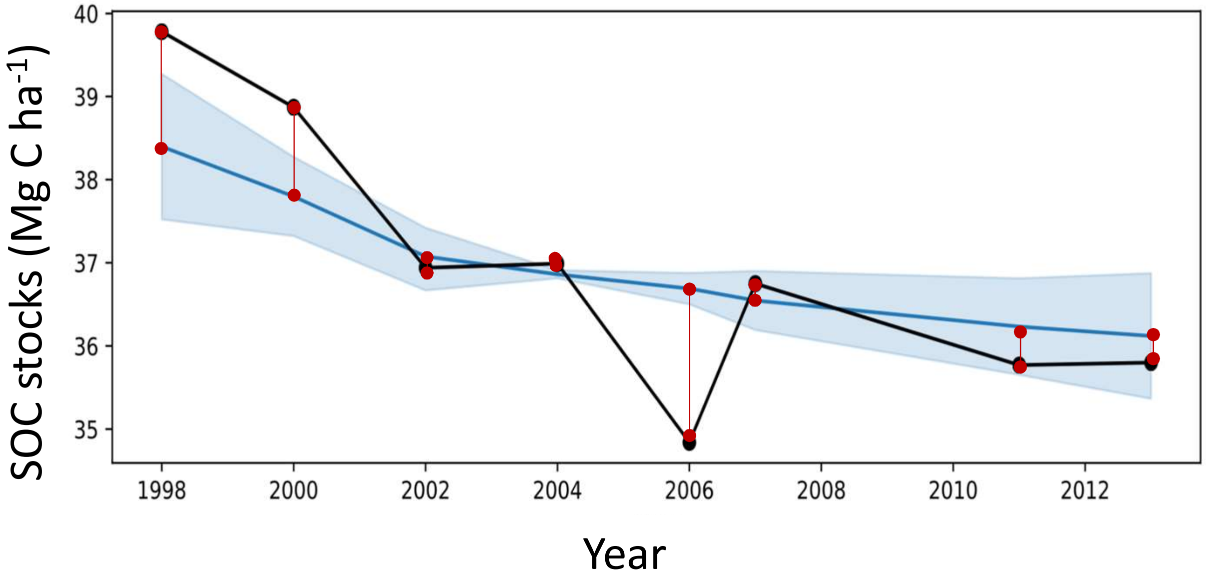


Jolivet et al., 2018

Tier 3 methods

- Model-based

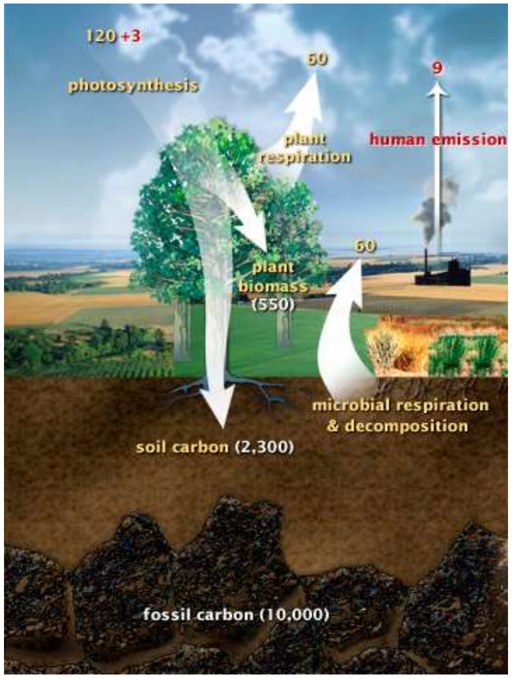
Field data to **evaluate** model performance



Advantages

Advantages

- Capture **complexity** of the system and diversity of practices, e.g., climate and disturbances effects

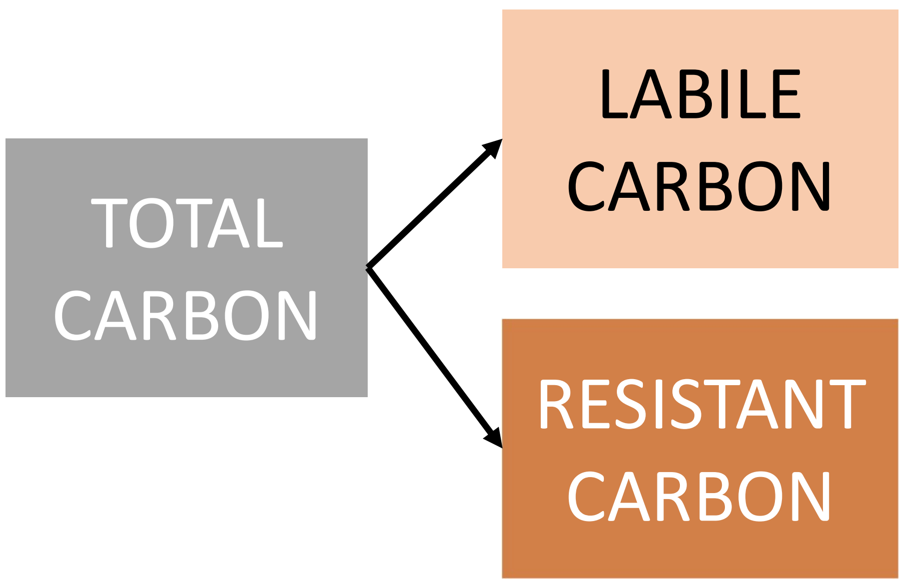


Advantages

- Higher spatial and temporal **resolution**

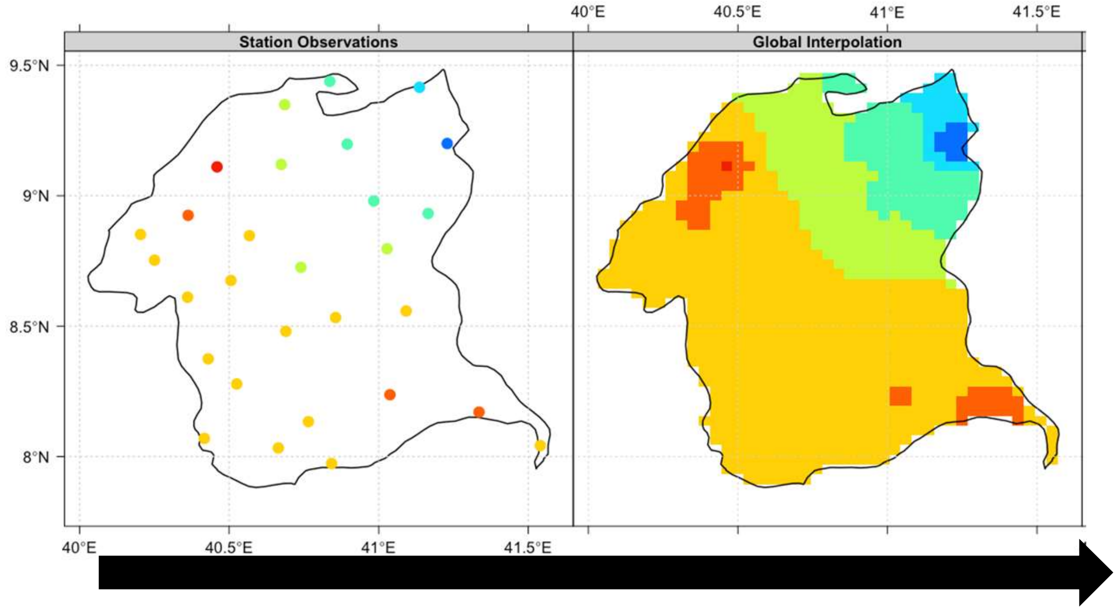
Advantages

- Improved **completeness**: coverage of land areas and/or carbon pools



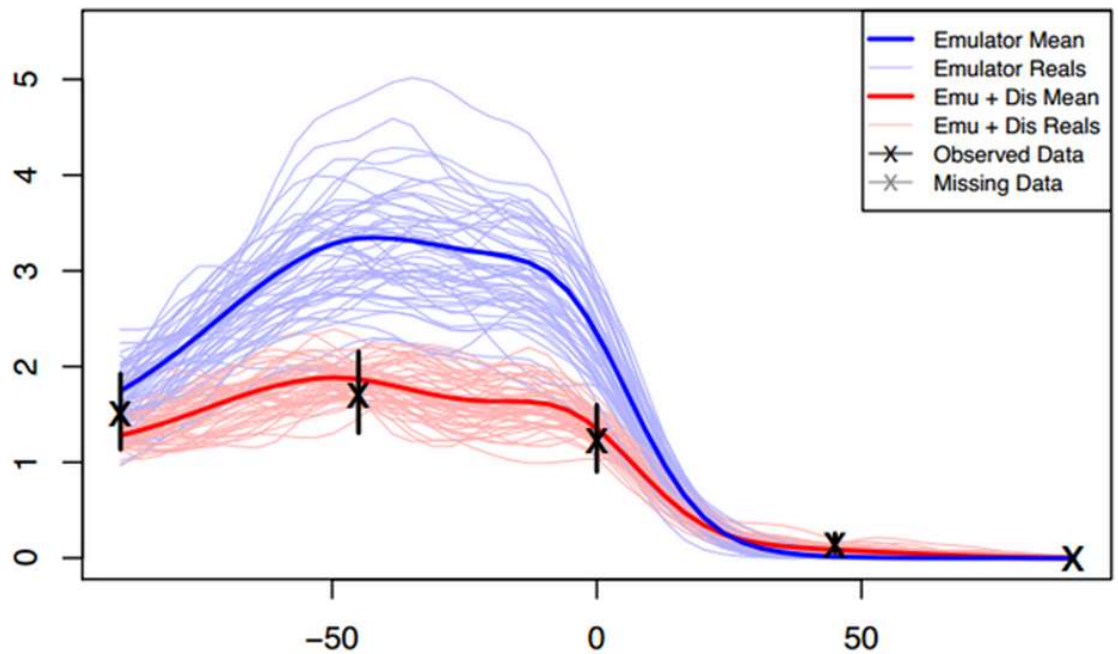
Advantages

- **Cost-efficient** compared to Tier 2 (which may need extensive data collection)



Advantages

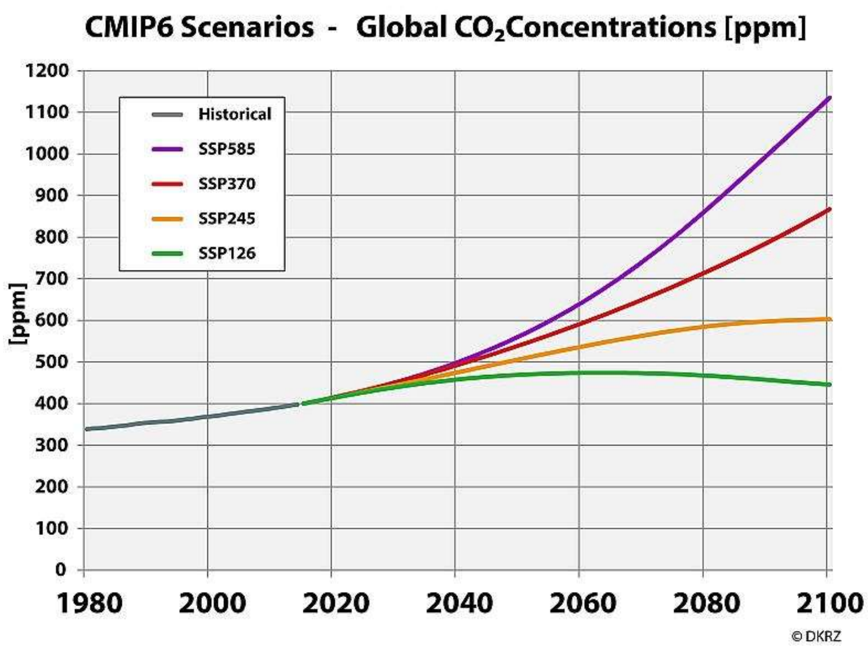
- Improved **uncertainty assessment**



Lane et al., 2014

Advantages

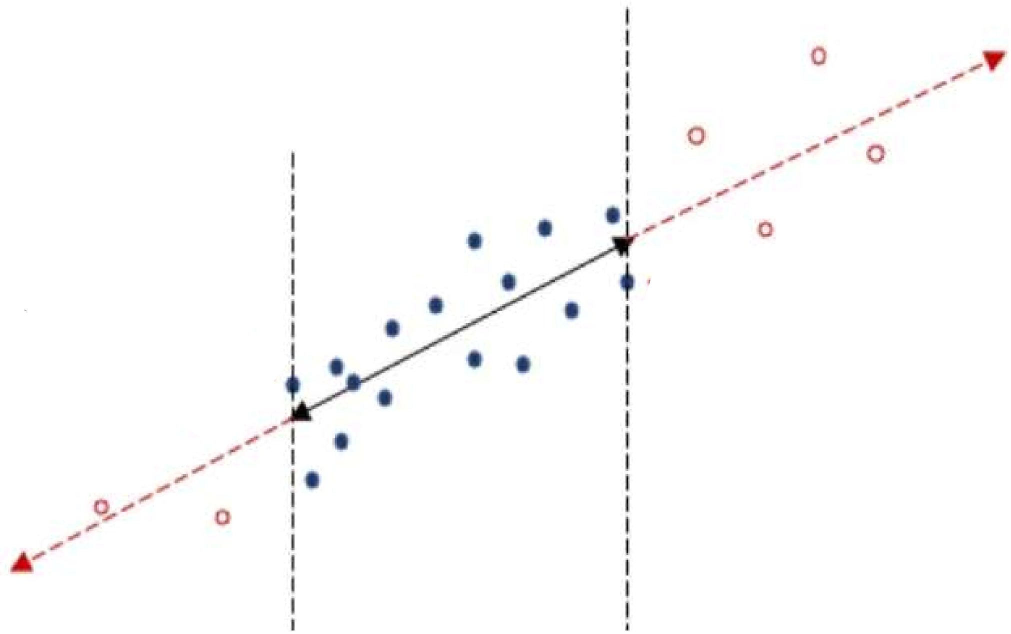
- **Predict**: better assessment of the impacts of mitigation efforts and policy measures



O'Neill et al. 2016

Advantages

- Improved **time-series consistency** for past and future projections



Limitations

Limitations

• *“Models are a way to increase the power of data”*: they still need a lot of **data** as input and for evaluation

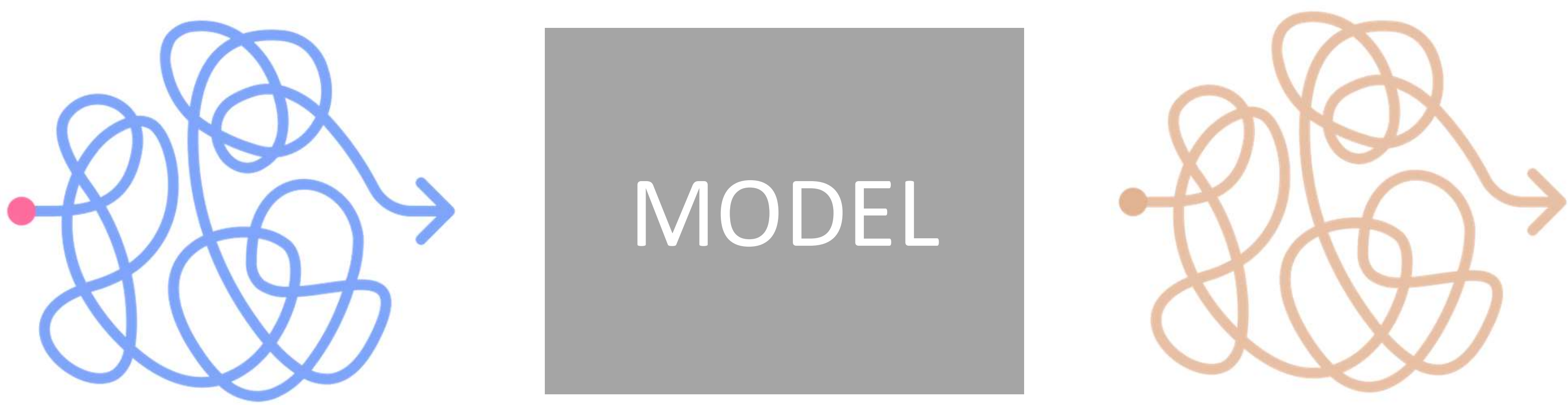
IPCC, 2010

Limitations

- *"Models are a simplified representation of reality":*
they are still associated with **uncertainty** and errors

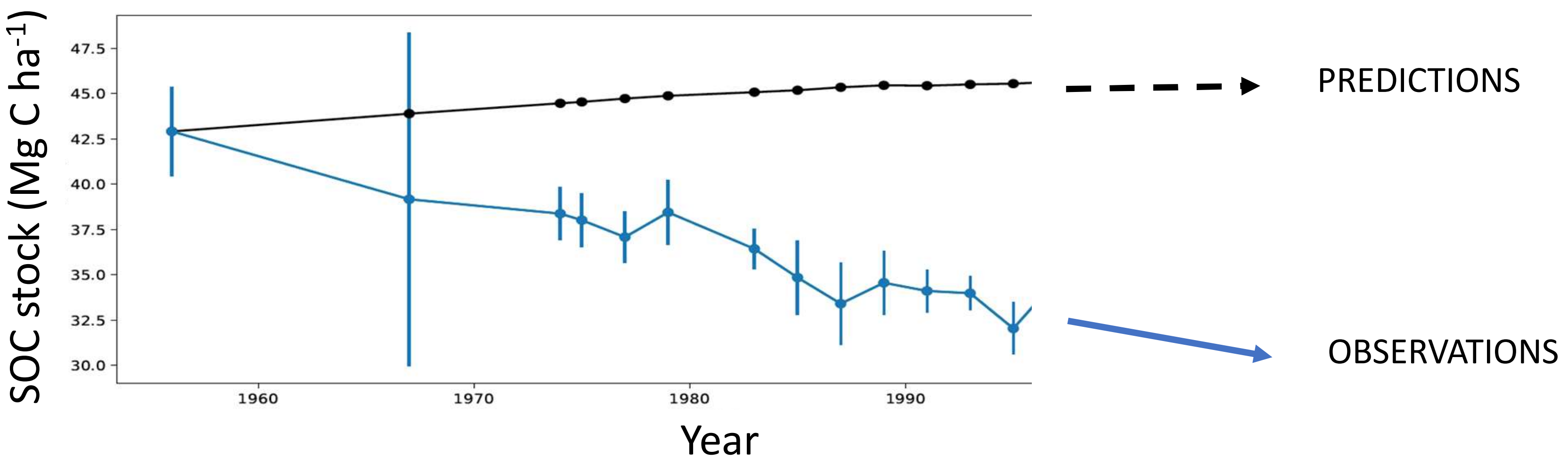
Limitations

- Uncertainty IN → uncertainty OUT



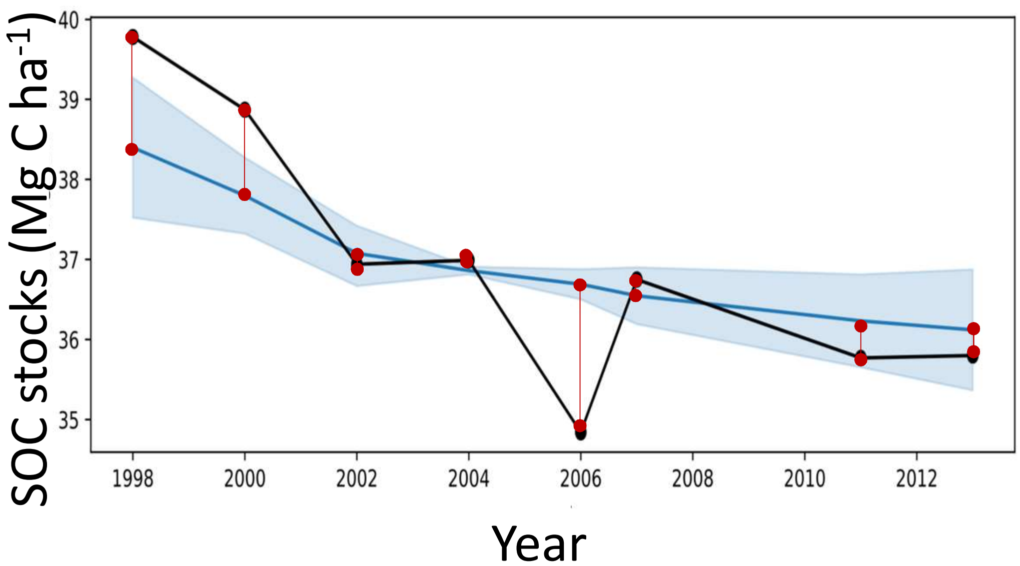
Limitations

- **Incorrect use** can lead to high errors and biases (e.g., application outside their domain, incorrect evaluation)



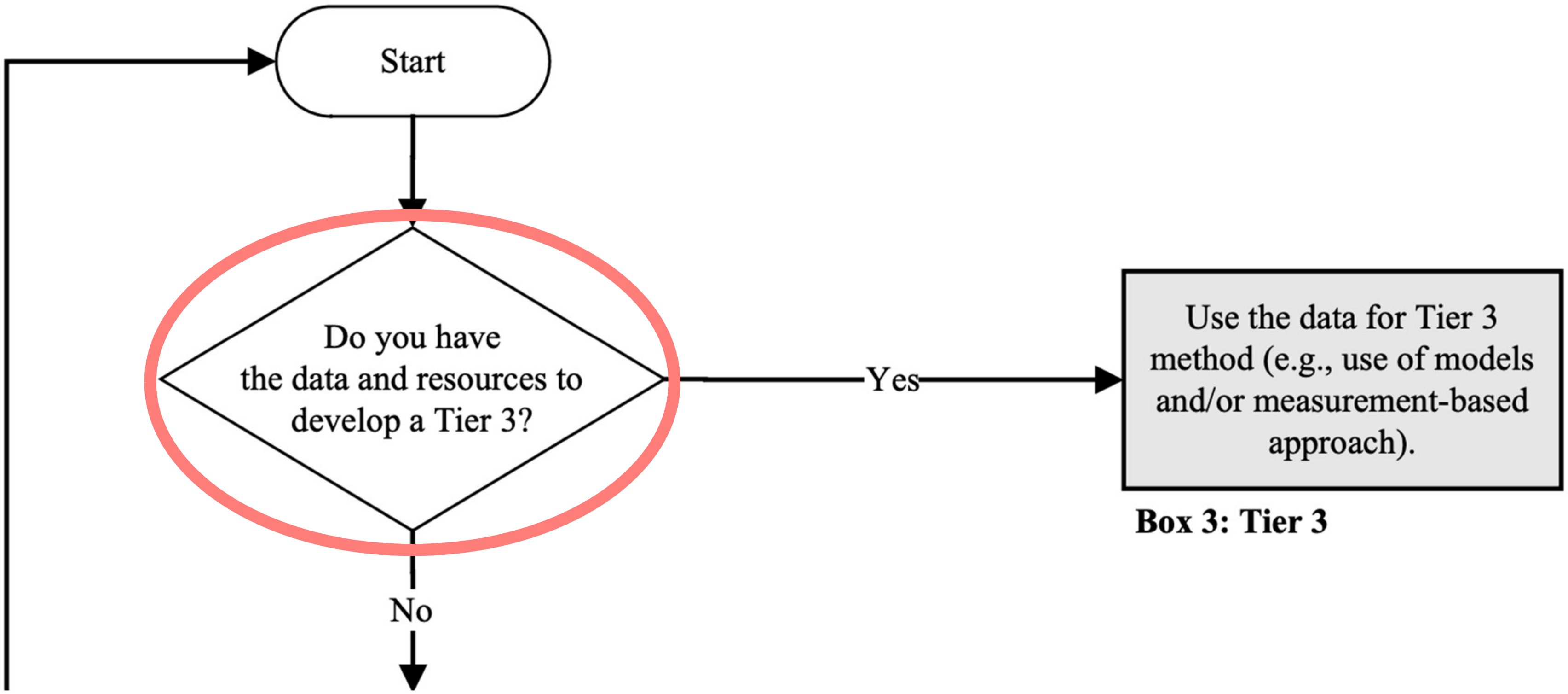
Limitations

- **Technical difficulties** to calibrate and implement



QUESTIONS?

When to use a Tier 3 approach?



IPCC Guidelines, 2006

1 Soil organic carbon models

2 Advantages and limitations

3 Steps of modeling

4 Case study

1. Select/develop a model
2. Evaluate with calibration data
3. Identify model input
4. Quantify uncertainties
5. Implement the model
6. Evaluate with independent data
7. Reporting and documentation

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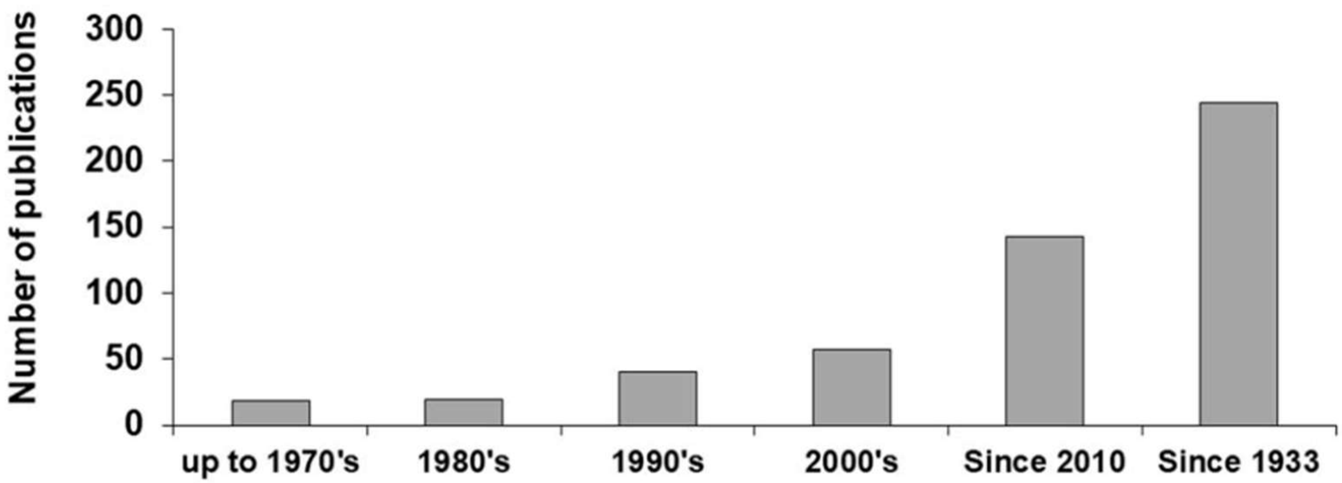
1 Select/develop a model

Model selection

1 Select/develop a model

Model selection

More than **200** soil carbon models are available

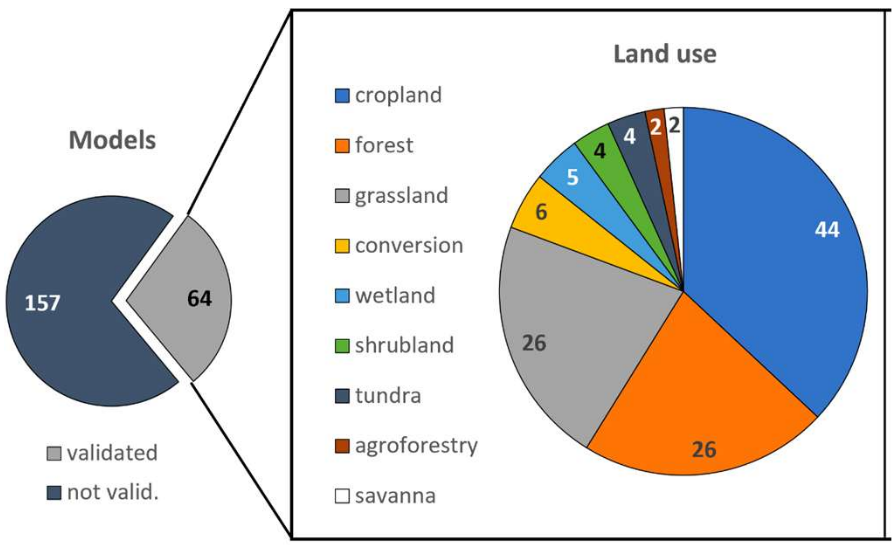


Le Noe et al., 2023

1 Select/develop a model

Model selection

Validated for the desired **land-use**

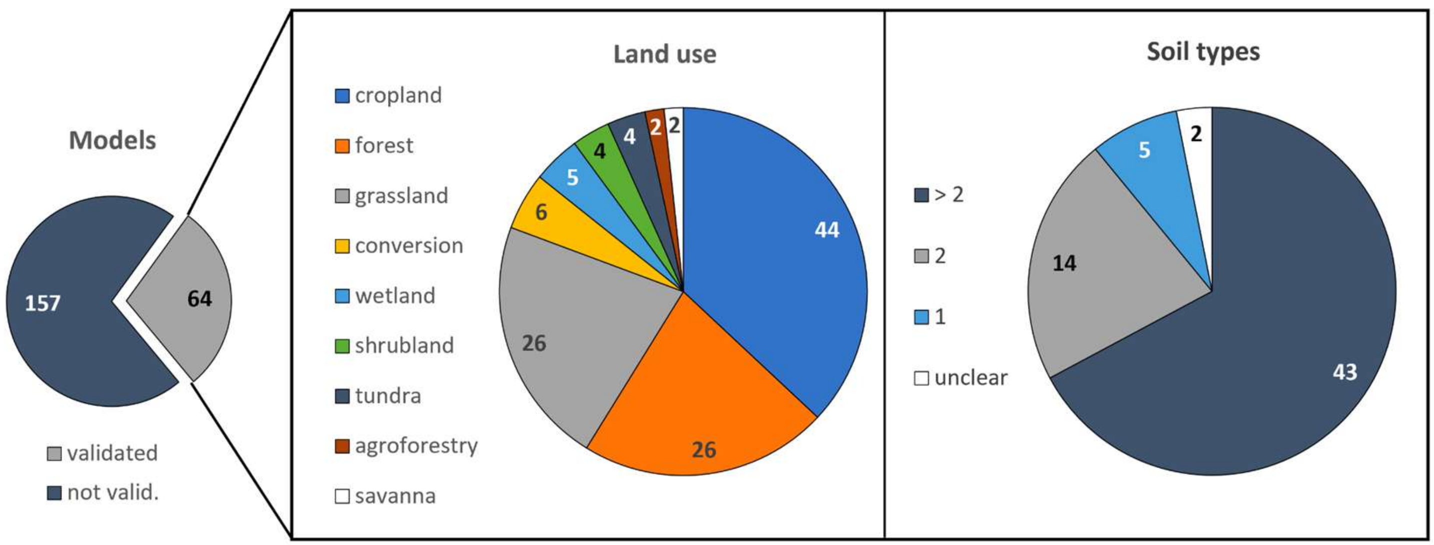


Garsia et al., 2023

1 Select/develop a model

Model selection

Validated for the desired **pedo-climatic** conditions



Garsia et al., 2023

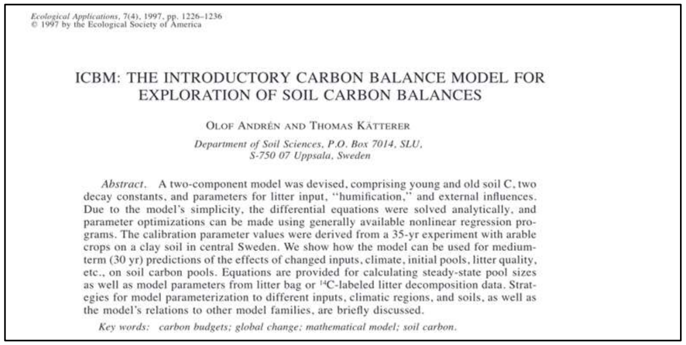
1 Select/develop a model

Model selection

Availability of the necessary **resources** for implementation

$$\frac{dY}{dt} = i - rk_1Y$$

$$\frac{dO}{dt} = hrk_1Y - rk_2O,$$



Ecological Applications, 7(4), 1997, pp. 1226–1236

ICBM: THE INTRODUCTORY CARBON BALANCE MODEL FOR EXPLORATION OF SOIL CARBON BALANCES

Olof Andrén and Thomas Kätterer

Department of Soil Sciences, P.O. Box 7014, SLU, S-750 07 Uppsala, Sweden

Abstract. A two-component model was devised, comprising young and old soil C, two decay constants, and parameters for litter input, "humification," and external influences. Due to the model's simplicity, the differential equations were solved analytically, and parameter optimizations can be made using generally available nonlinear regression programs. The calibration parameter values were derived from a 35-yr experiment with arable crops on a clay soil in central Sweden. We show how the model can be used for medium-term (30 yr) predictions of the effects of changed inputs, climate, initial pools, litter quality, etc., on soil carbon pools. Equations are provided for calculating steady-state pool sizes as well as model parameters from litter bag or ^{14}C-labeled litter decomposition data. Strategies for model parameterization to different inputs, climatic regions, and soils, as well as the model's relations to other model families, are briefly discussed.

Key words: carbon budgets; global change; mathematical model; soil carbon.

1 Select/develop a model

Model selection

Availability of the **data** required (see Step 3)

Climate data	Soil data	Land use- management data
1. Monthly rainfall(mm) 2. Average monthly mean air temperature (ºC) 3. Monthly open pan evaporation (mm)/evapotranspiration (mm)	1. Total Initial 0—30cm SOC stocks (t C ha^{-1}) 2. Initial C stocks of the different pools (t C ha^{-1}): DPM, RPM, BIO, HUM, IOM 3. Clay content (%) at simulation depth.	1. Monthly Soil cover (binary: bare vs. vegetated) 2. Irrigation (to be added to rainfall amounts) 3. Monthly Carbon inputs from plant residue (aboveground + roots + rhizodeposition), (t C ha^{-1}) 4. Monthly Carbon inputs from organic fertilizers and grazing animals' excretion (t C ha^{-1}) 5. DPM/RPM ratio, an estimate of the decomposability of the incoming plant material

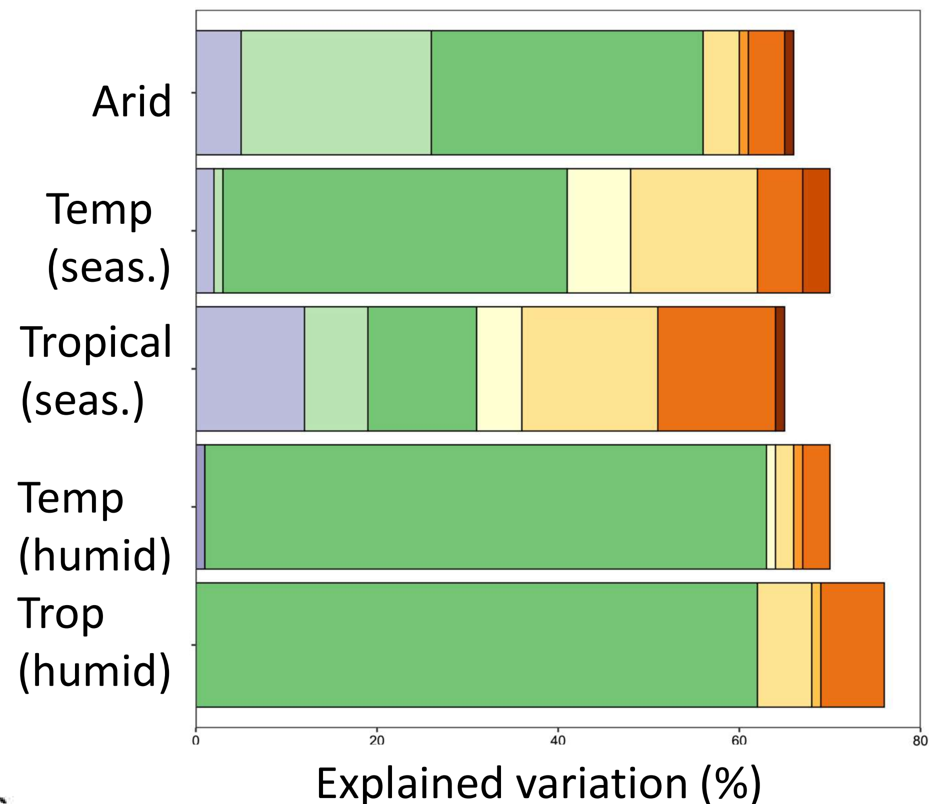
1 Select/develop a model

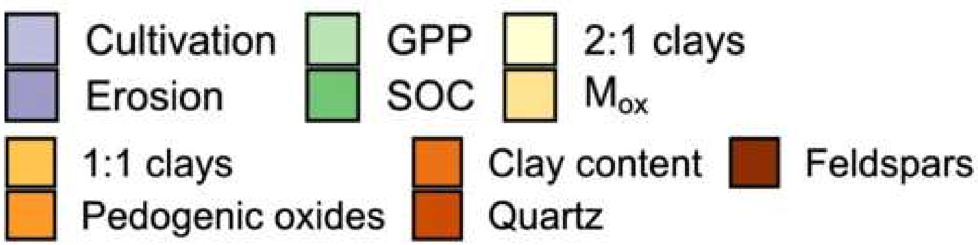
Model adaptation

1 Select/develop a model

Model adaptation

Factors that influence SOC persistence depend on pedo-climatic conditions





Von Fromm et al., 2023

1 Select/develop a model

Model adaptation

Some human activities may be important in some countries, not in other

1. Select/develop a model
2. **Evaluate with calibration data**
3. Identify model input
4. Quantify uncertainties
5. Implement the model
6. Evaluate with independent data
7. Reporting and documentation

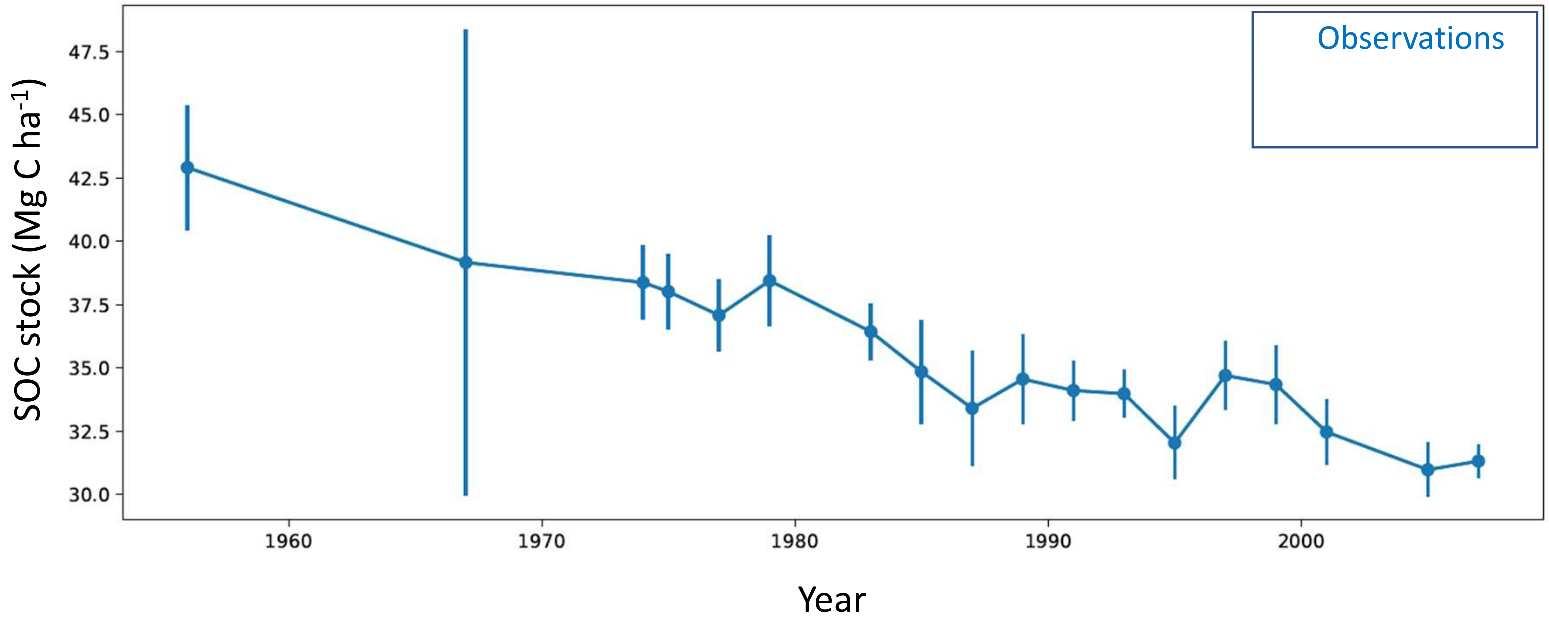
2 Evaluate with calibration data

Demonstrate that the model **effectively simulates measured trends** for a variety of conditions in the category of interest

3 Steps of modeling

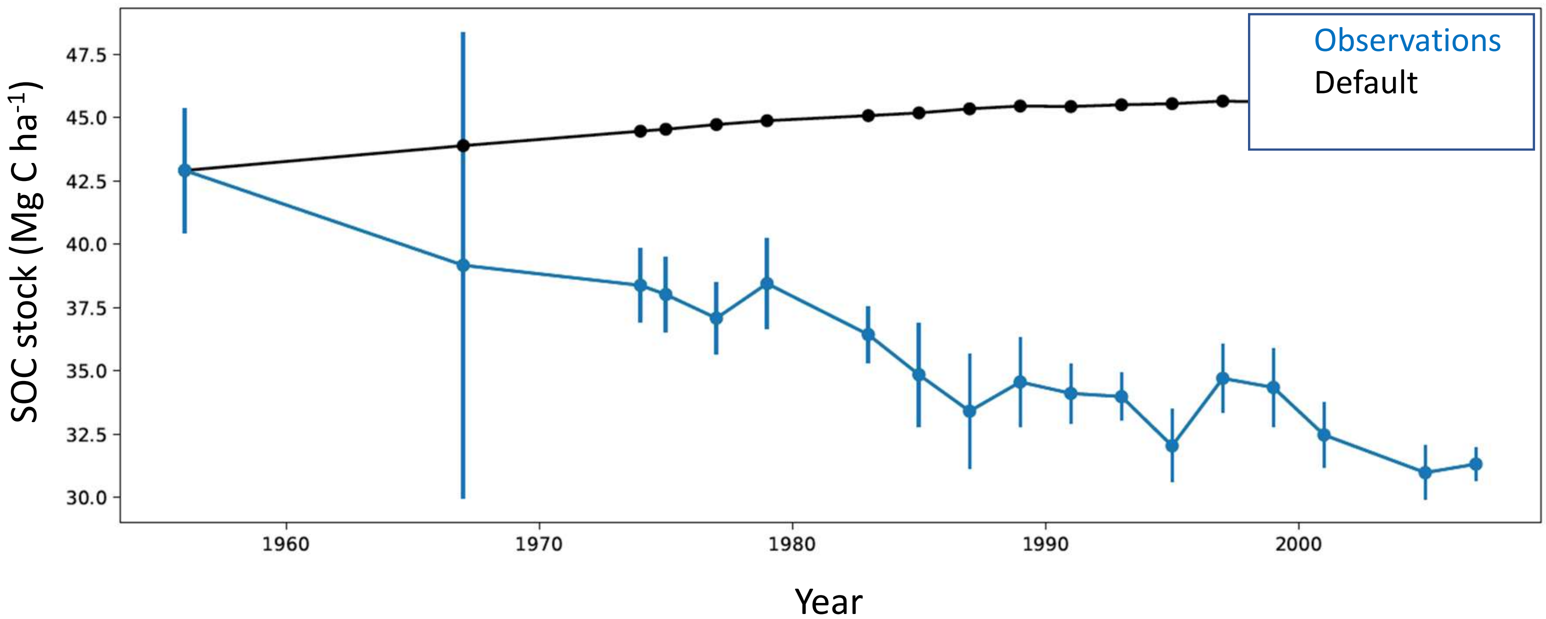
2 Evaluate with calibration data

Evaluation with statistical and graphical tests



2 Evaluate with calibration data

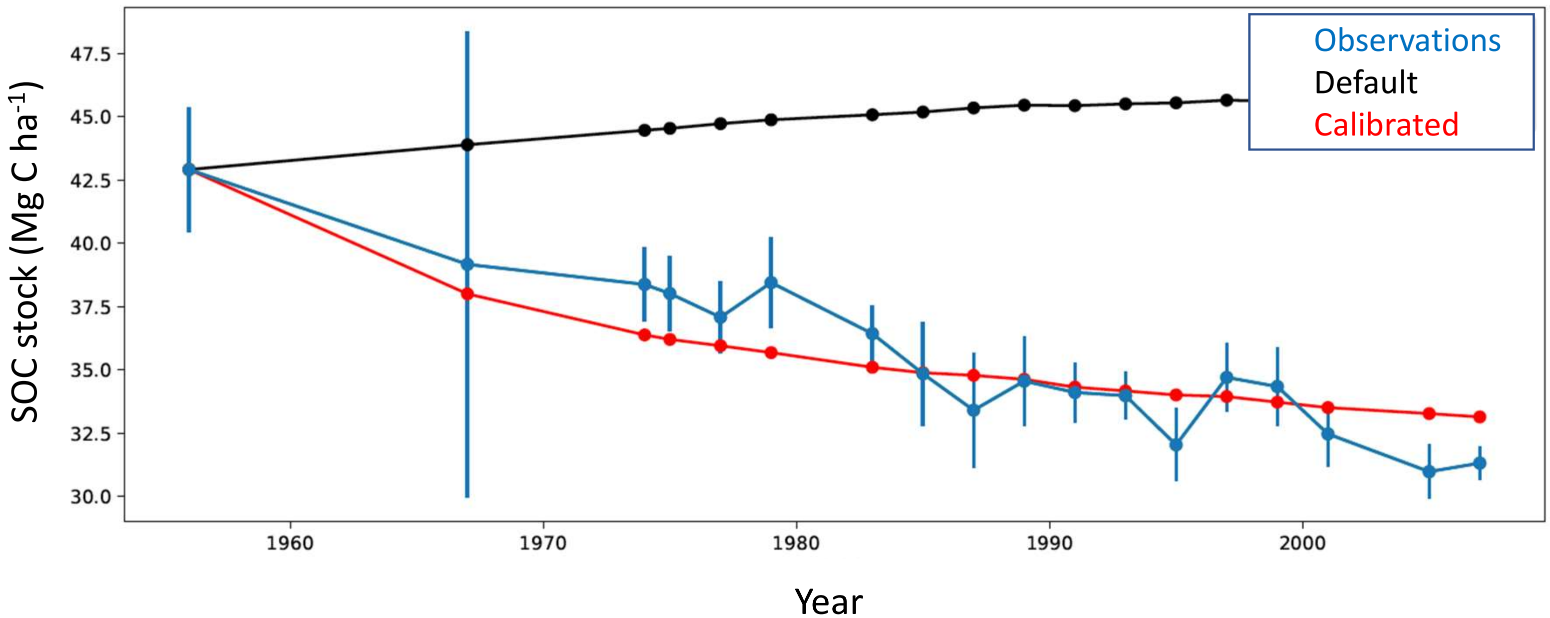
Evaluation with statistical and graphical tests



k = 0.165

2 Evaluate with calibration data

Evaluation with statistical and graphical tests



k = 0.165

k = 0.604

2 Evaluate with calibration data

Examples of statistics for evaluation

- Root mean squared error, $RMSE$
- Coefficient of determination, R^2
- Willmott index of agreement, d

2 Evaluate with calibration data

Examples of statistics for evaluation

- Root mean squared error, $RMSE$ ✔
- Coefficient of determination, R^2 ✔
- Willmott index of agreement, d ✔

The model effectively simulates measured trends

2 Evaluate with calibration data

- If the evaluation is not satisfactory, re-calibrate or change model
- Model evaluation needs to be in the reporting documentation to justify the use of a particular model

QUESTIONS?

1 Select/develop a model

2 Evaluate with calibration data

3 Identify model input

4 Quantify uncertainties

5 Implement the model

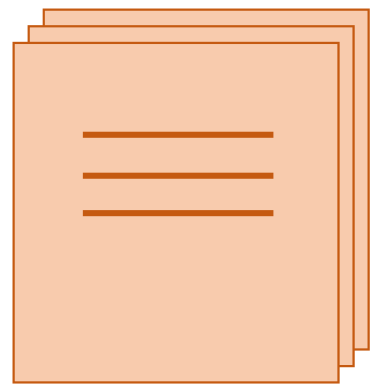
6 Evaluate with independent data

7 Reporting and documentation

3 Identify model input

Spatial and temporal data on:

- Climate
- Soil
- Vegetation
- Land-management
- Disturbances



3 Identify model input

Spatial and temporal data on:

- Climate
- Soil
- Vegetation
- Land-management
- Disturbances

3 Identify model input

Spatial and temporal data on:

- Climate
  - Temperature (surface or soil)
  - Precipitation
  - Potential evapotranspiration
  - Soil moisture

3 Identify model input

Spatial and temporal data on:

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3 Identify model input

Spatial and temporal data on:

- Climate
- Soil
- Vegetation
- Land-management
- Disturbances

3 Identify model input

Spatial and temporal data on:

- Climate
- Soil
  - Clay content
  - Initial SOC stocks in the soil pools
  - pH
  - C:N ratio
  - $CaCO_3$ content

3 Identify model input

Spatial and temporal data on:

- Climate
- Soil
- Vegetation
- Land-management
- Disturbances

3 Identify model input

Spatial and temporal data on:

- Climate
- Soil
- Vegetation
  - Litter input
  - Woody debris
  - Animal manure

3 Identify model input

Spatial and temporal data on:

- Climate
- Soil
- Vegetation
- Land-management
- Disturbances

3 Identify model input

Spatial and temporal data on:

- Climate
- Soil
- Vegetation
- Land-management
  - Agricultural practices (e.g., tillage, cover cropping)
  - Forest practices (e.g., clear-cut, thinning)

3 Identify model input

Spatial and temporal data on:

- Climate
- Soil
- Vegetation
- Land-management
- Disturbances

3 Identify model input

Spatial and temporal data on:

- Climate
- Soil
- Vegetation
- Land-management
- Disturbances
  - Fires
  - Insects outbreaks

3 Identify model input

Spatial and temporal data on:

- Climate
- Soil
- Vegetation
- Land-management
- Disturbances

Consistent with spatial-temporal scale of the model!

1. Select/develop a model
2. Evaluate with calibration data
3. Identify model input
4. **Quantify uncertainties**
5. Implement the model
6. Evaluate with independent data
7. Reporting and documentation

4 Quantify uncertainties

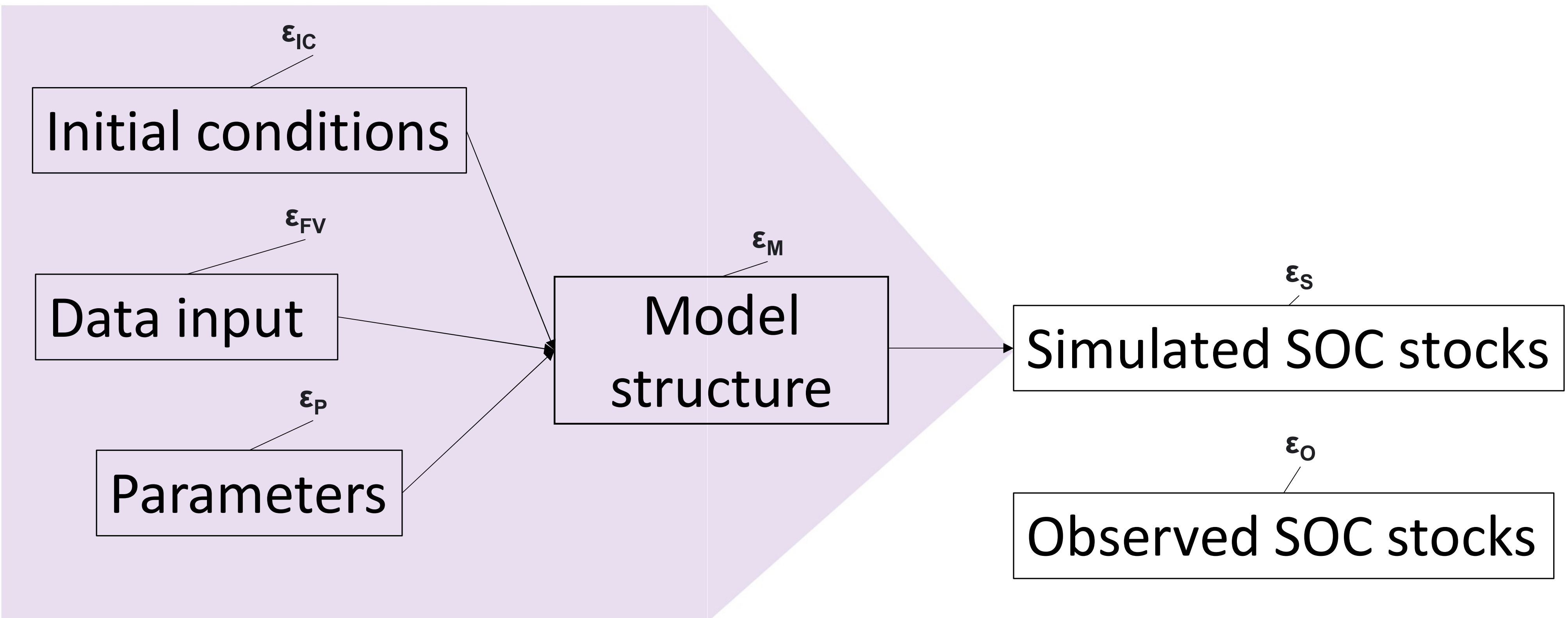
- Uncertainty measures the **confidence** of the model estimate
- Imperfect knowledge of activities and processes

→ uncertainties in the structure, parametrization and inputs

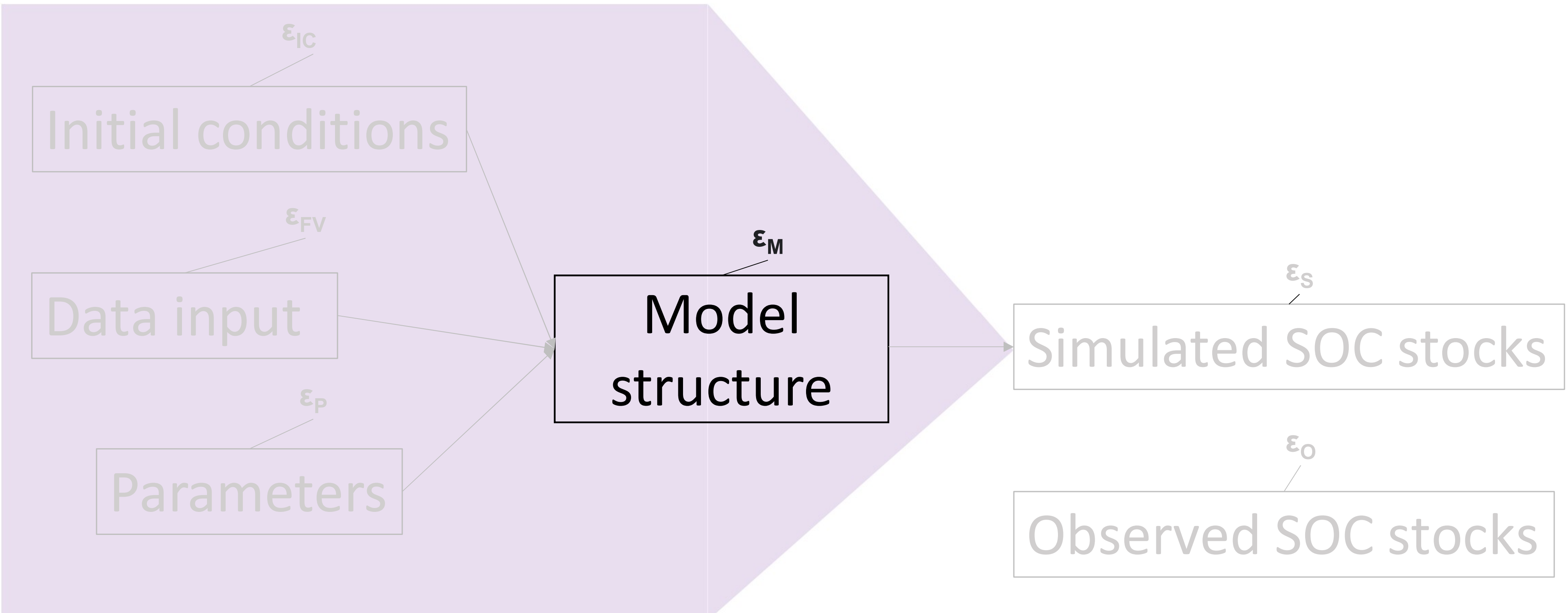
Methods to conduct these analyses: see IPCC Guidelines (2006) Volume 1 Chapter 3

3 Steps of modeling

4 Quantify uncertainties

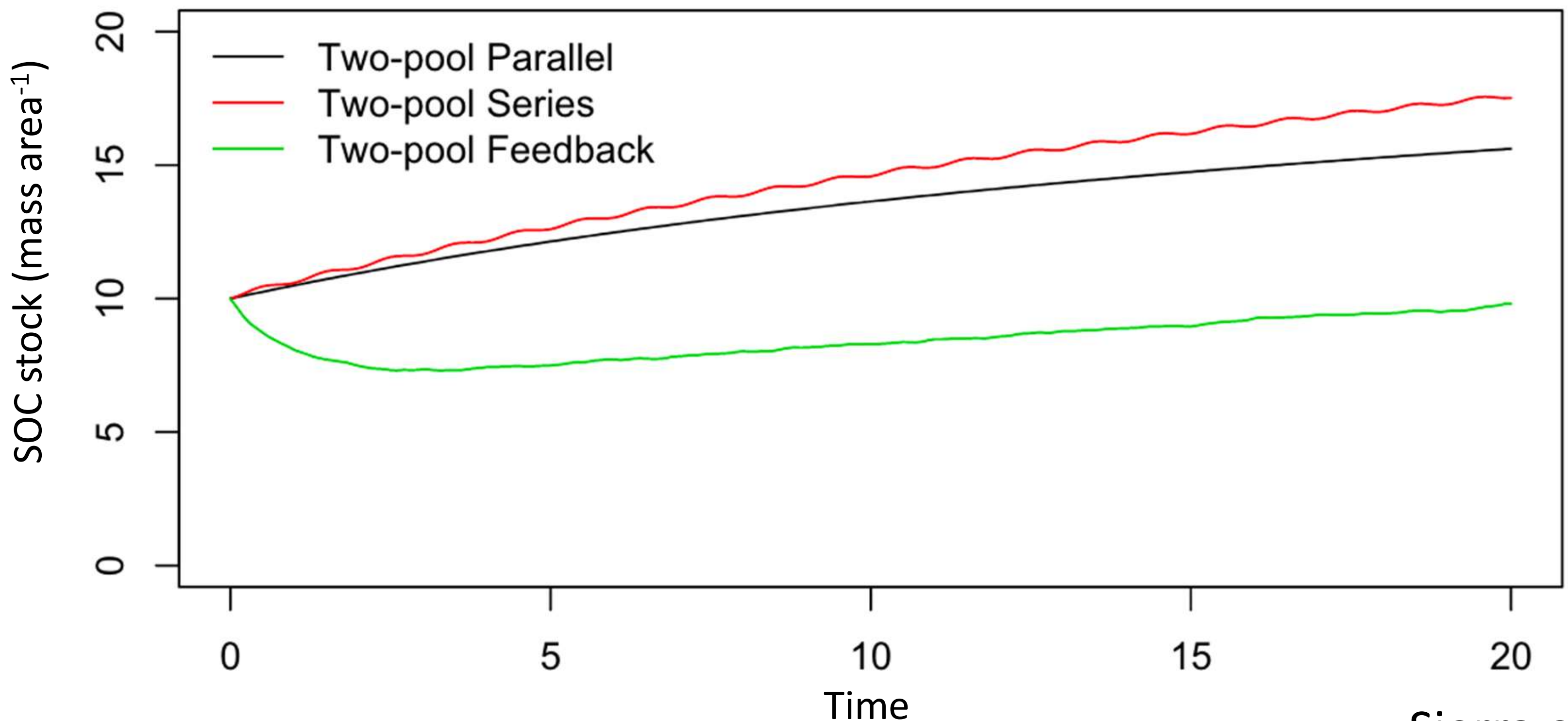


4 Quantify uncertainties



4 Quantify uncertainties

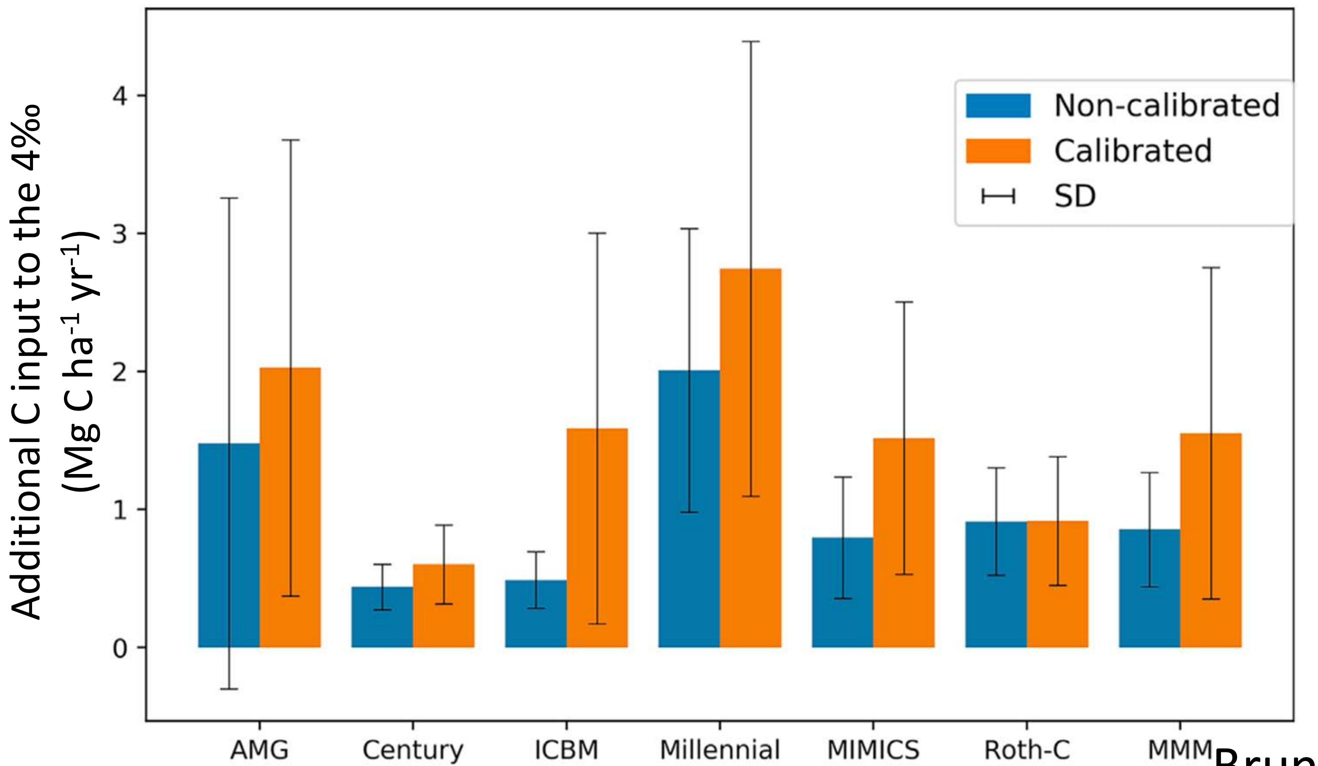
Model structure



Sierra et al., 2012

4 Quantify uncertainties

Model structure



Bruni et al, 2022

4 Quantify uncertainties

Model structure

Multi-modeling approaches can help assessing the effect of model structure on the simulations

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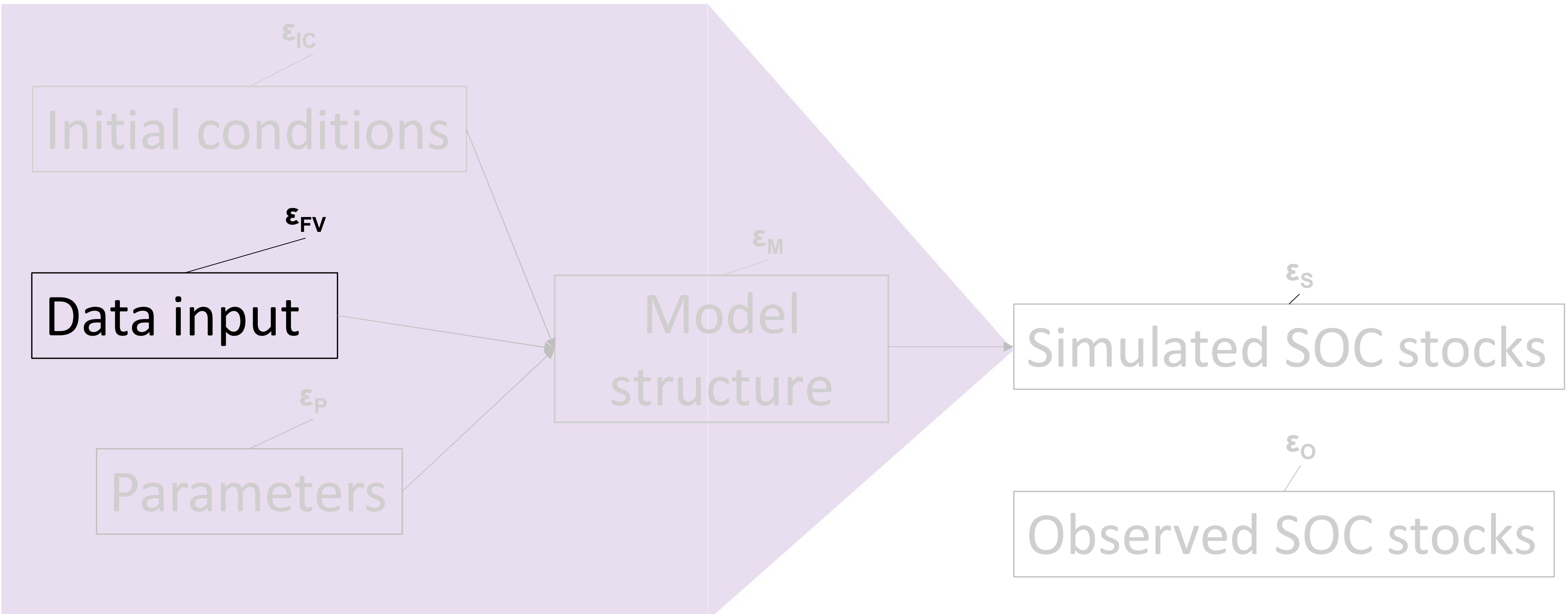
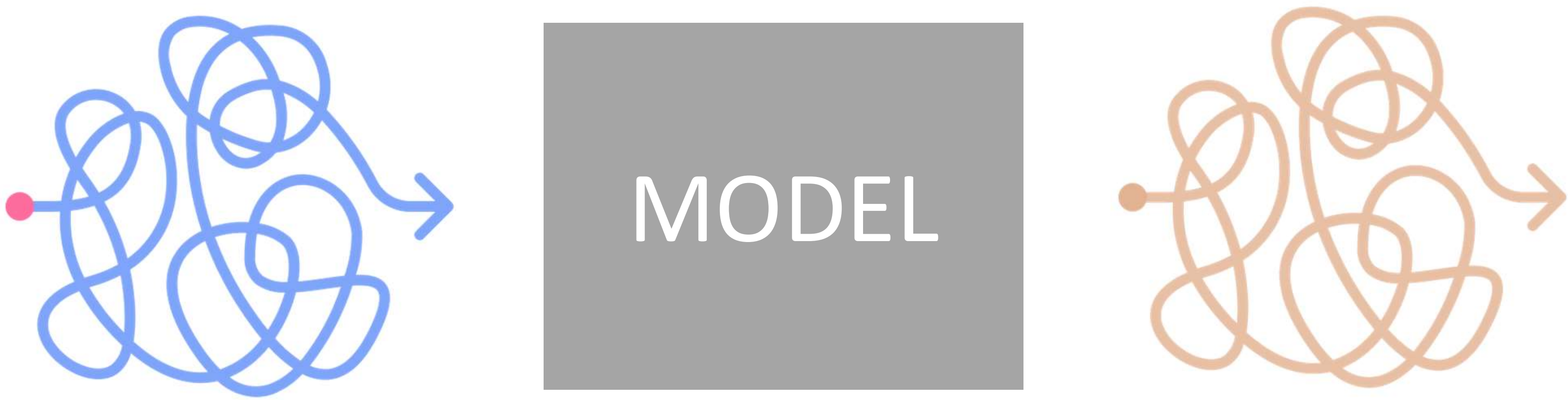
3 Steps of modeling

4 Quantify uncertainties



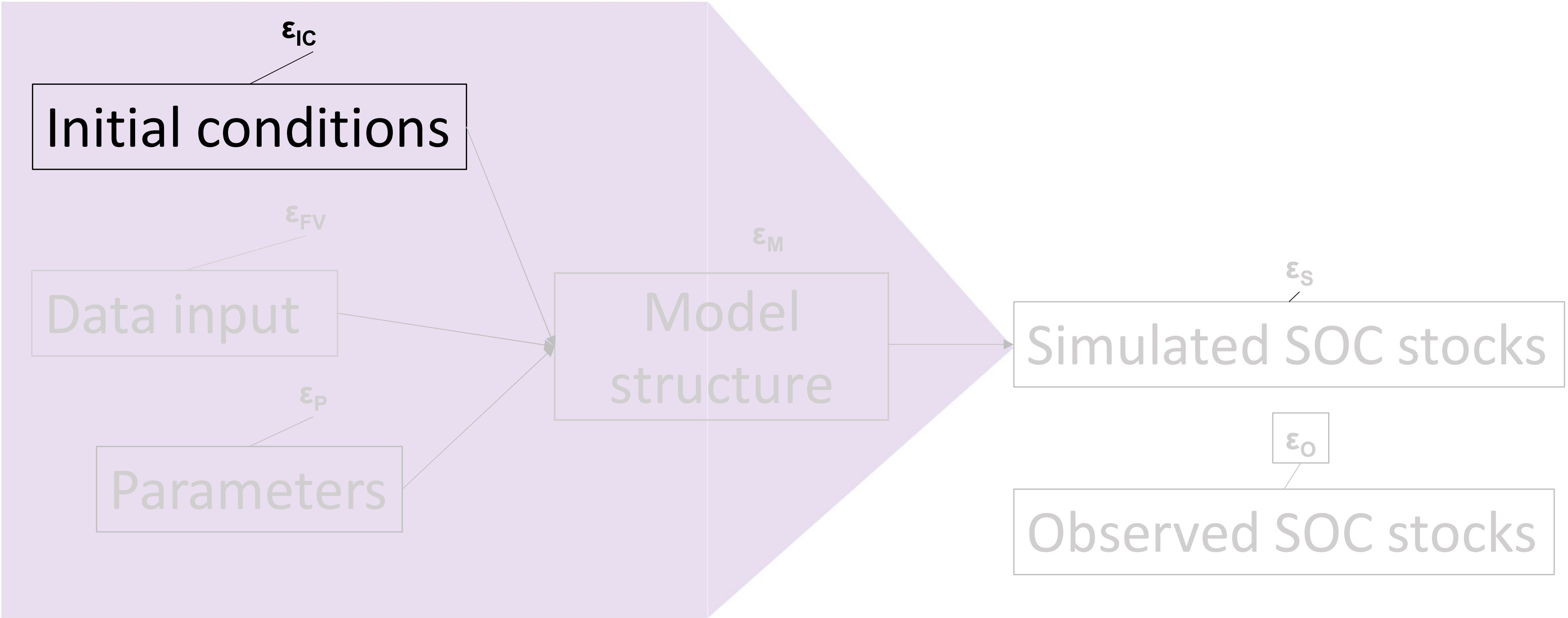
4 Quantify uncertainties

Data input



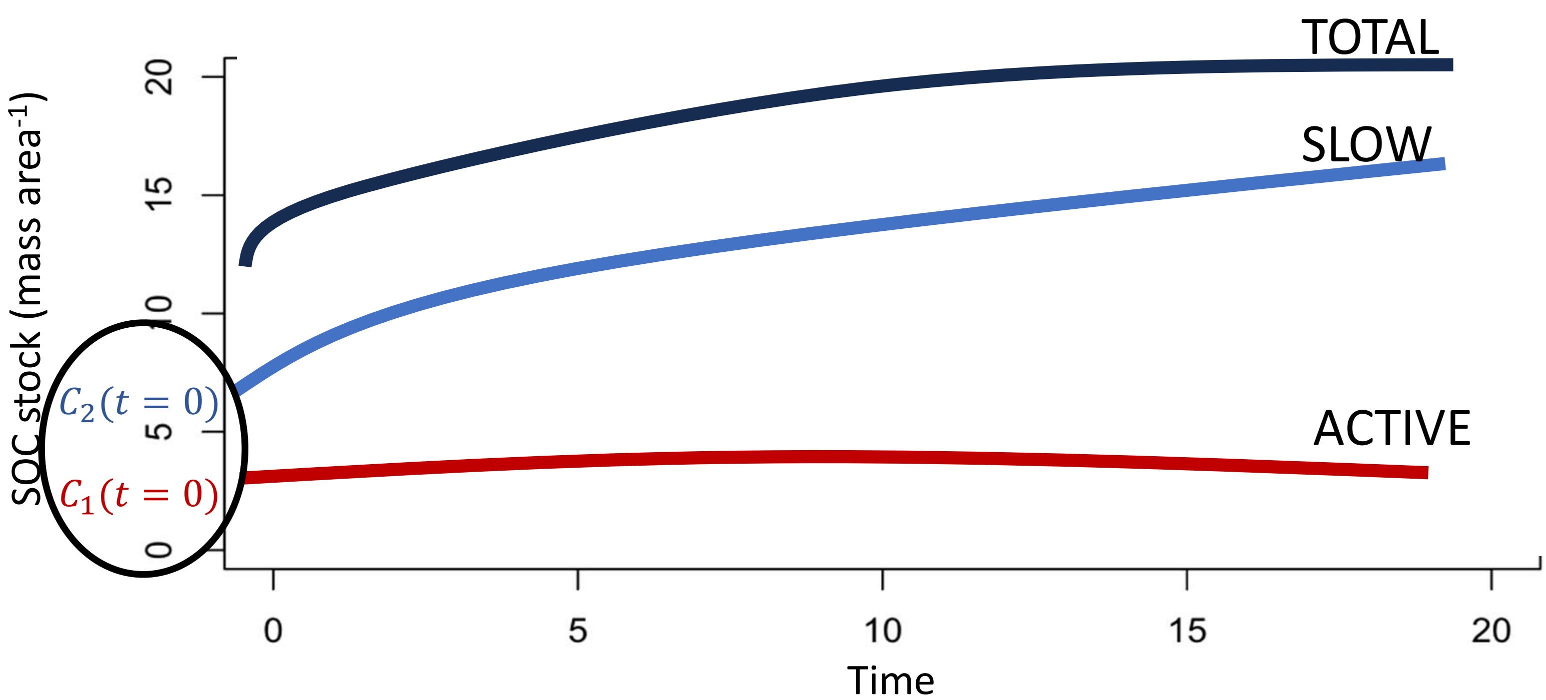
3 Steps of modeling

4 Quantify uncertainties



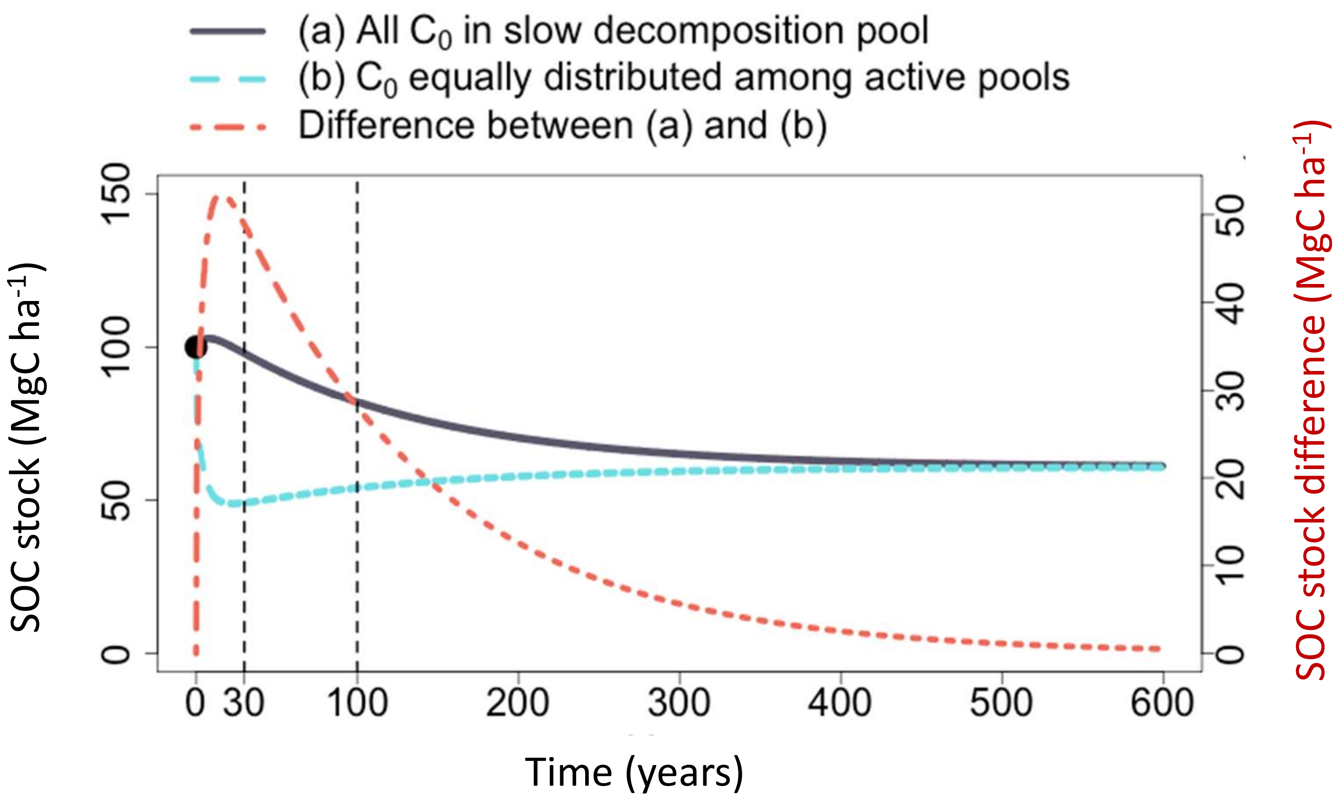
4 Quantify uncertainties

Initial conditions



4 Quantify uncertainties

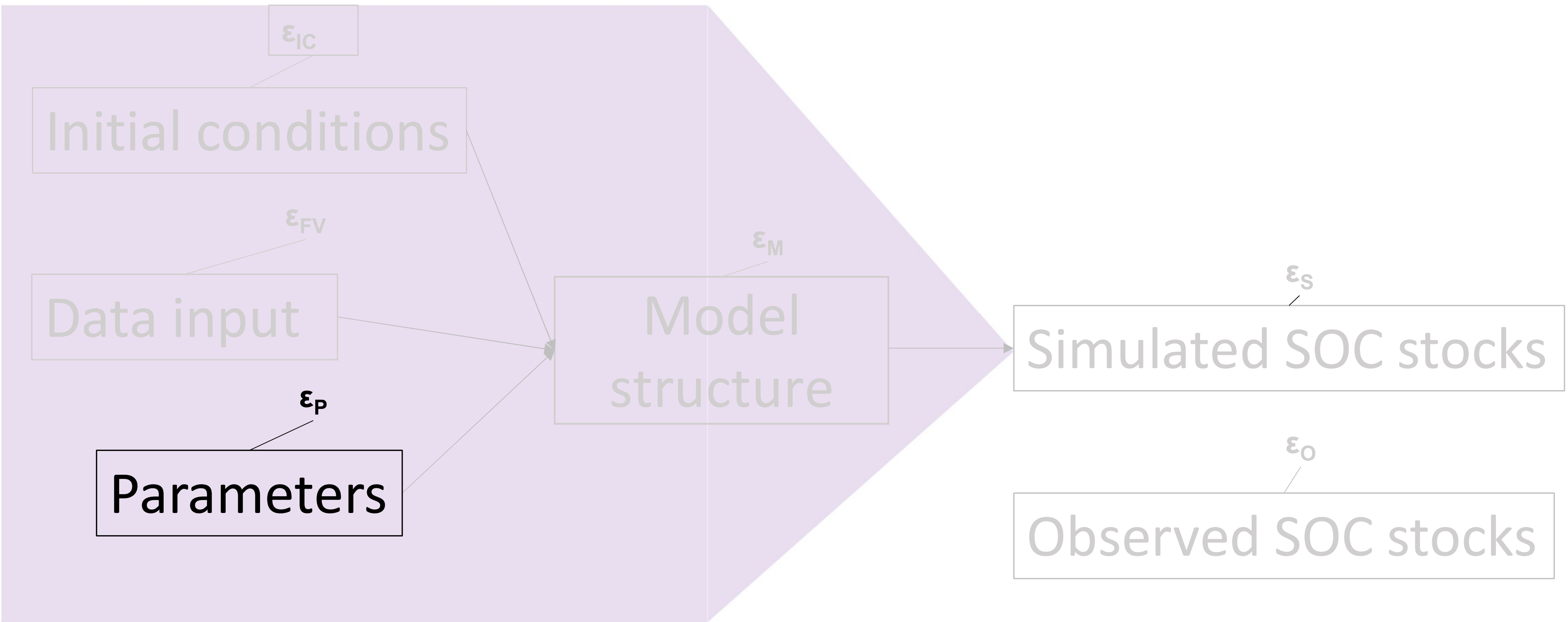
Initial conditions



Bruni et al, in prep.

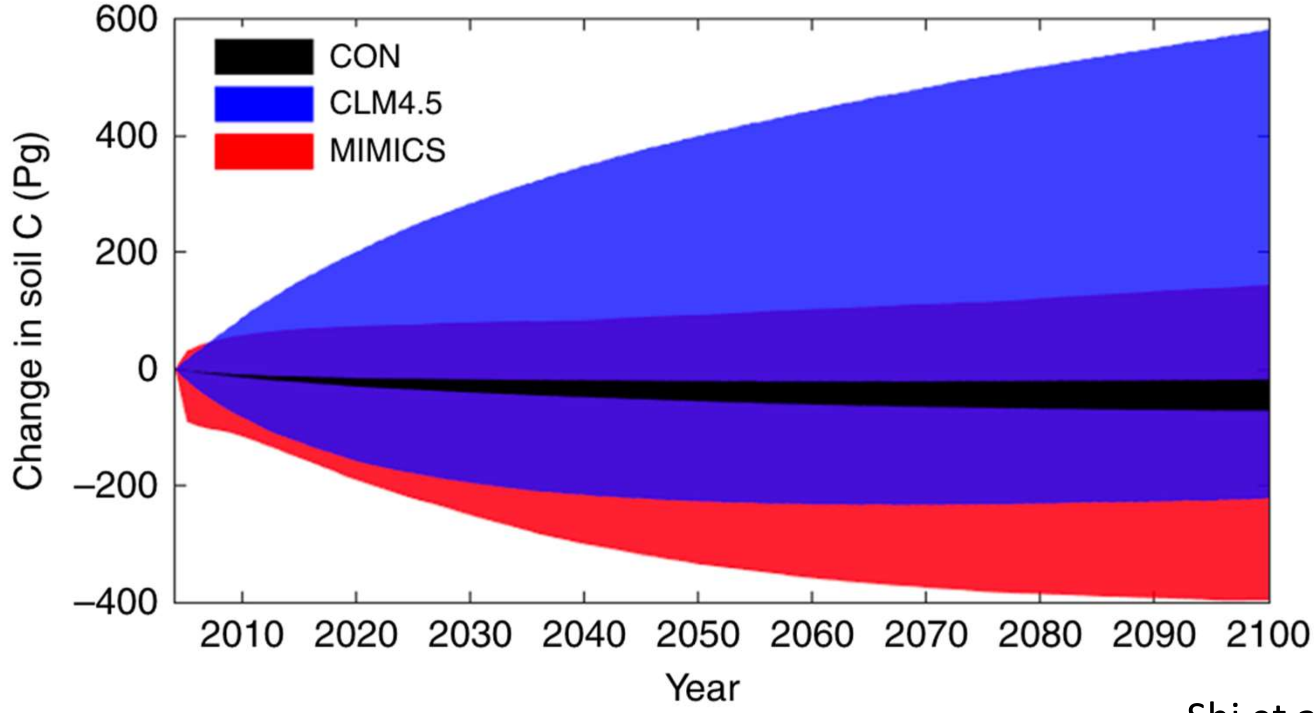
3 Steps of modeling

4 Quantify uncertainties



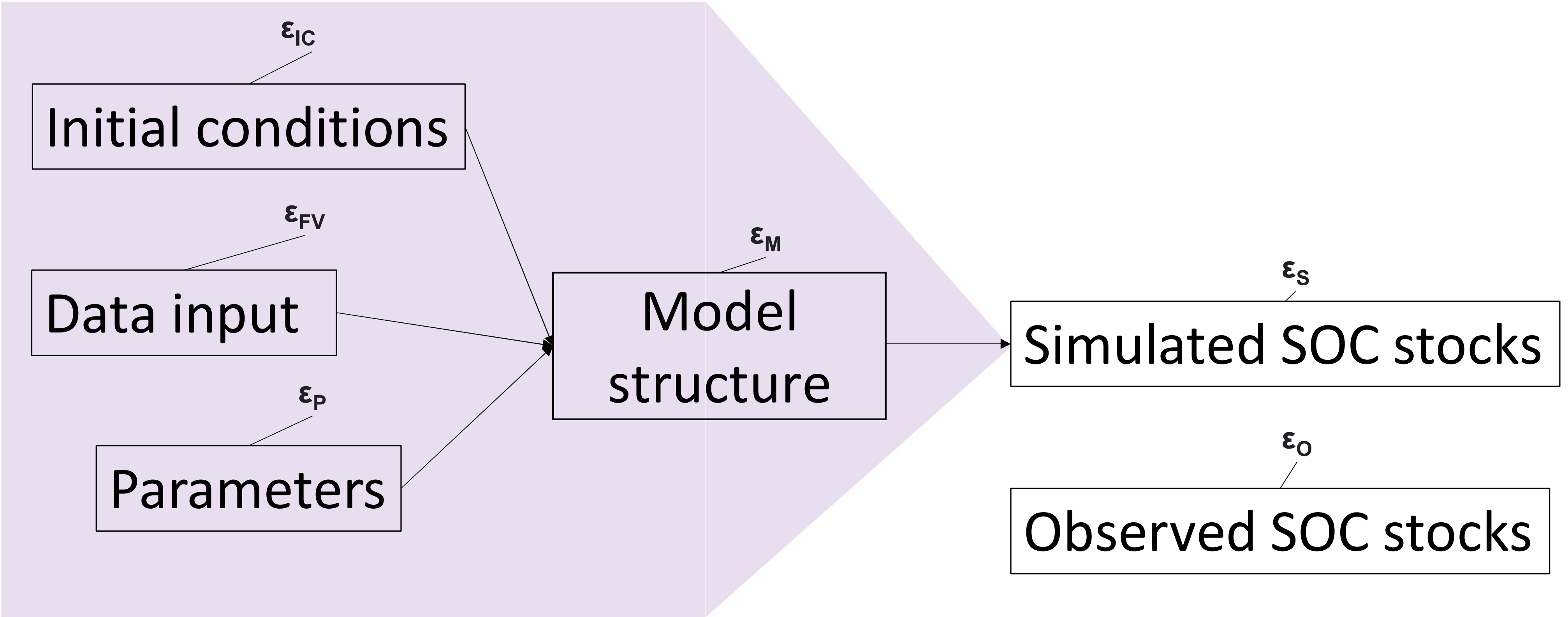
4 Quantify uncertainties

Parameters



Shi et al., 2018

4 Quantify uncertainties

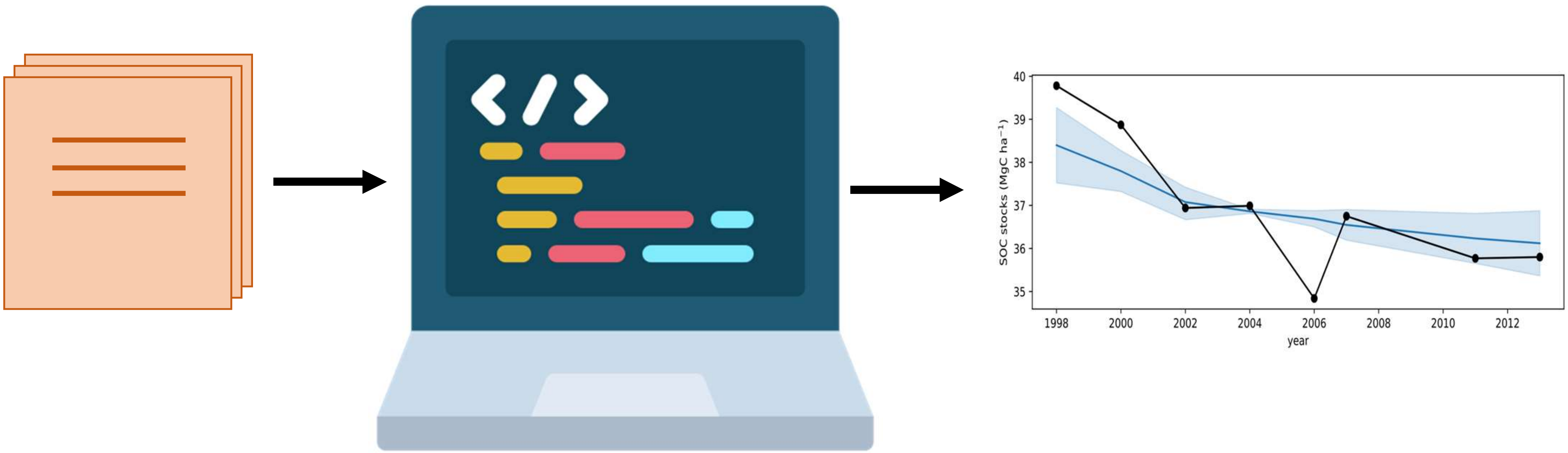


QUESTIONS?

1. Select/develop a model
2. Evaluate with calibration data
3. Identify model input
4. Quantify uncertainties
5. **Implement the model**
6. Evaluate with independent data
7. Reporting and documentation

5 Implement the model

- Run the model code on a computer



5 Implement the model

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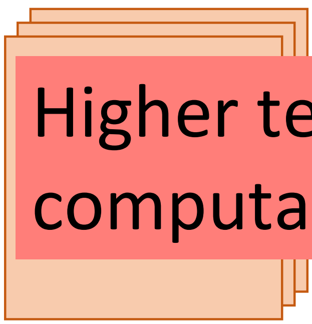
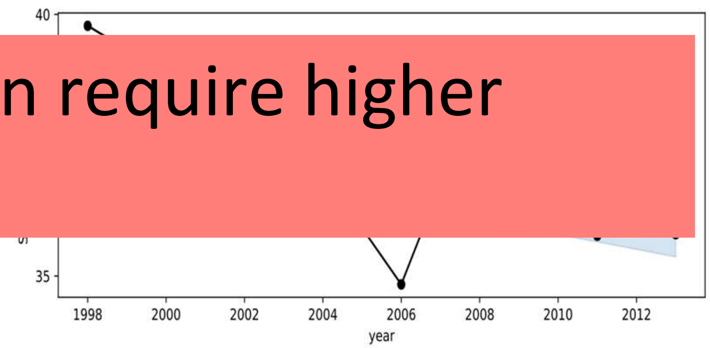




Higher temporal and spatial resolution require higher computational resources!

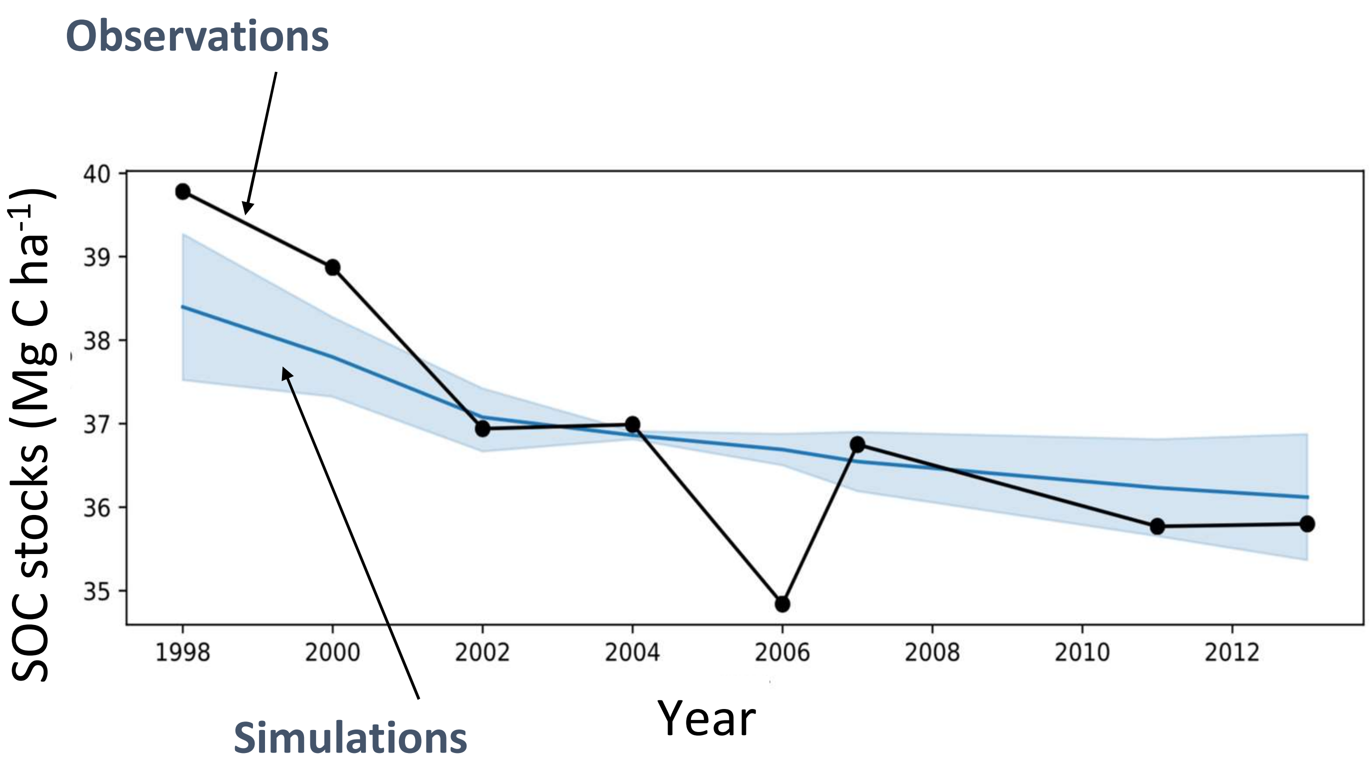
1. Select/develop a model
2. Evaluate with calibration data
3. Identify model input
4. Quantify uncertainties
5. Implement the model
6. **Evaluate with independent data**
7. Reporting and documentation

6 Evaluate with independent data

- **Independent** database means a database other than the one that was used for calibration of the parameters

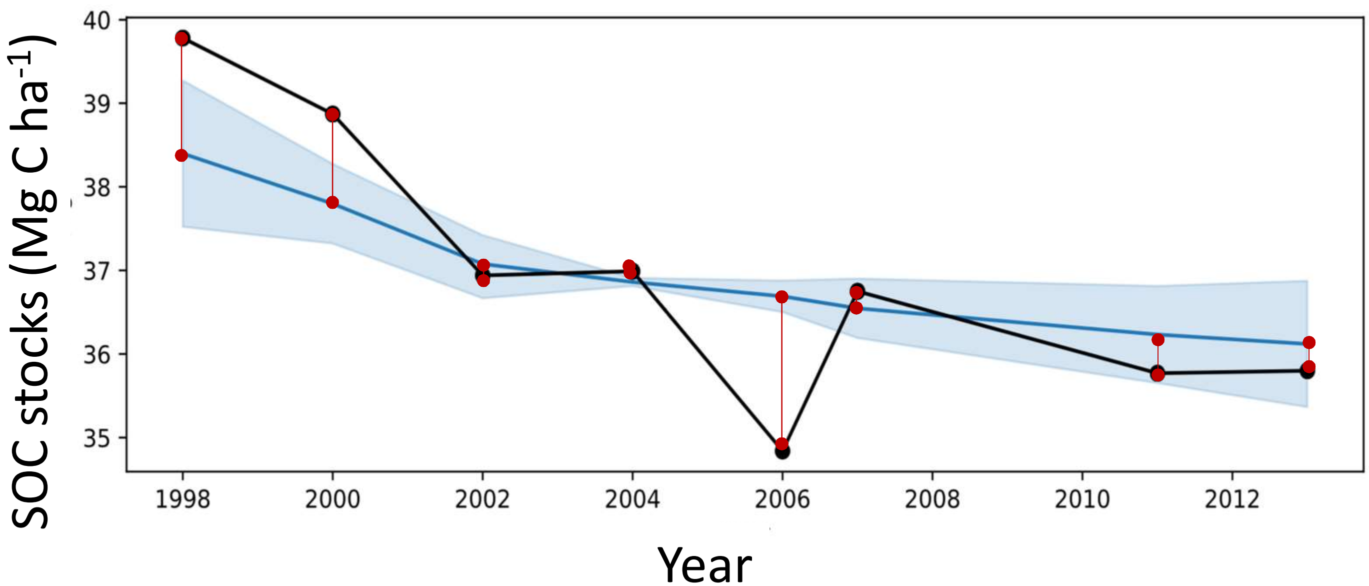
- Database of observations based on a **monitoring network** or research sites (~ similar to measurement-bases Tier 3, but with a lesser density)

6 Evaluate with independent data



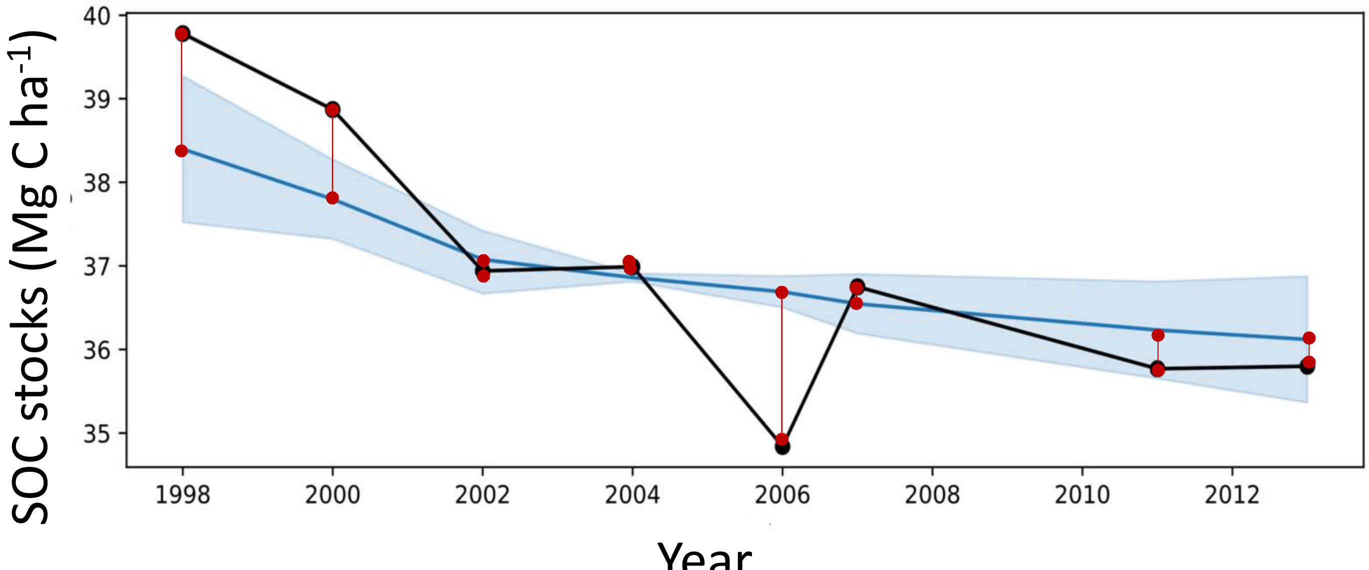
6 Evaluate with independent data

RMSE, R^2, d



6 Evaluate with independent data

RMSE, R^2, d



If evaluation is not satisfactory, go back to step 2, 3 or 1!

1 Select/develop a model

2 Evaluate with calibration data

3 Identify model input

4 Quantify uncertainties

5 Implement the model

6 Evaluate with independent data

7 Reporting and documentation

7 Reporting and documentation

Transparency: information needed to understand the model and assess its outputs

- Model description from **literature**
- Model assessment from the **evaluation**

QUESTIONS?

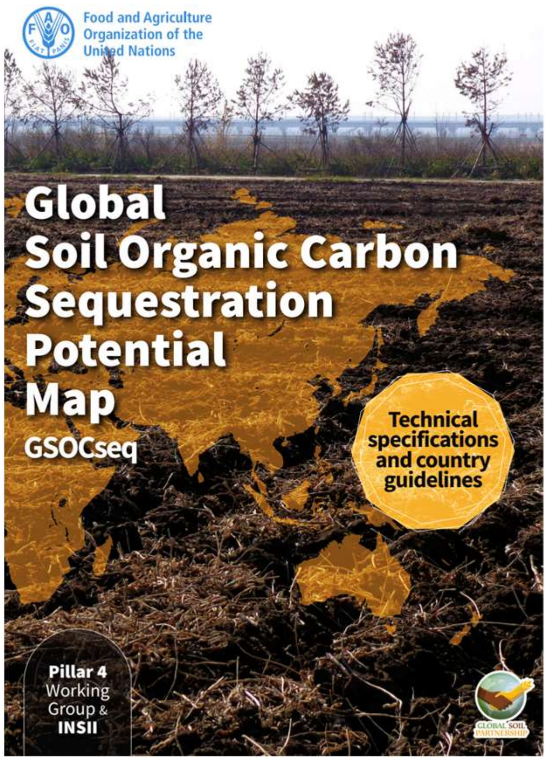
1 Soil organic carbon models

2 Advantages and limits

3 Steps of modeling

4 Case study

Example of a Tier 3 application



FAO, 2020

4 Case study

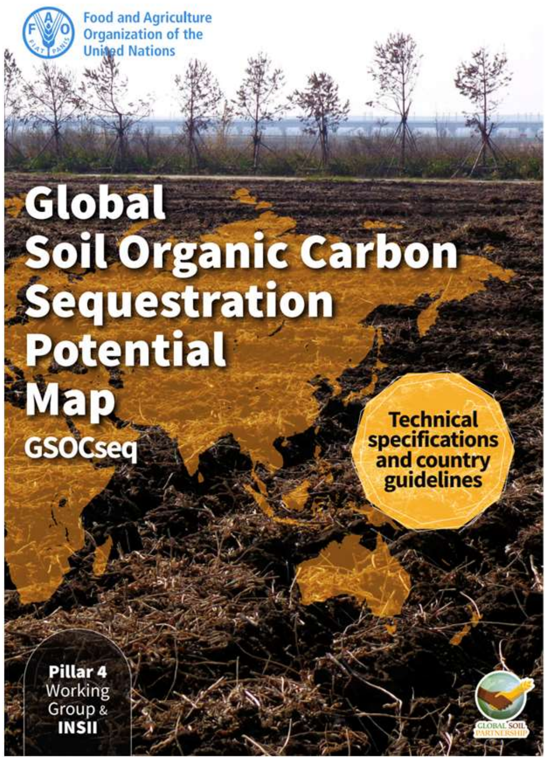
Example of a Tier 3 application

FAO guidelines

of Roth-C model application

to produce **national maps** of SOC sequestration potential in croplands

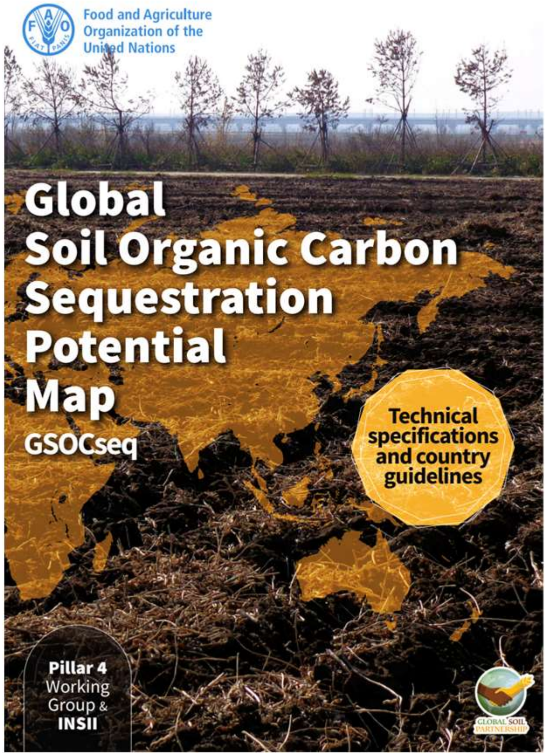
under different sustainable soil management practices



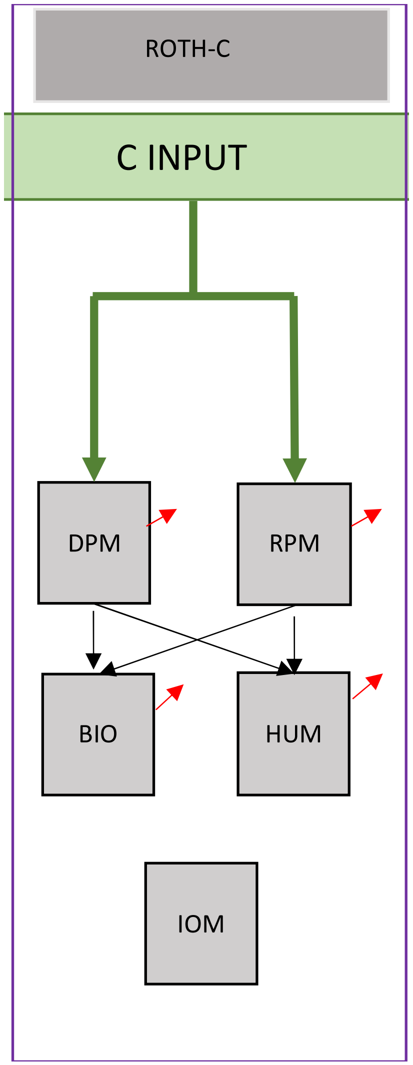
FAO, 2020

Example of a Tier 3 application

- ➢Procedure steps
- ➢Limitation of this case-study



FAO, 2020



Coleman and Jenkinson, 1996

Modeling procedure

- Gather the data input
- Determine the initial conditions
- Run the model for different management scenarios
- Generate SOC sequestration maps

Data requirements for Roth-C

Climate data	Soil data	Land use- management data
1. Monthly rainfall(mm) 2. Average monthly mean air temperature (ºC) 3. Monthly open pan evaporation (mm)/evapotranspiration (mm)	1. Total Initial 0–30cm SOC stocks (t C ha^{-1}) 2. Initial C stocks of the different pools (t C ha^{-1}): DPM, RPM, BIO, HUM, IOM 3. Clay content (%) at simulation depth.	1. Monthly Soil cover (binary: bare vs. vegetated) 2. Irrigation (to be added to rainfall amounts) 3. Monthly Carbon inputs from plant residue (aboveground + roots + rhizodeposition), (t C ha^{-1}) 4. Monthly Carbon inputs from organic fertilizers and grazing animals' excretion (t C ha^{-1}) 5. DPM/RPM ratio, an estimate of the decomposability of the incoming plant material

Modeling procedure

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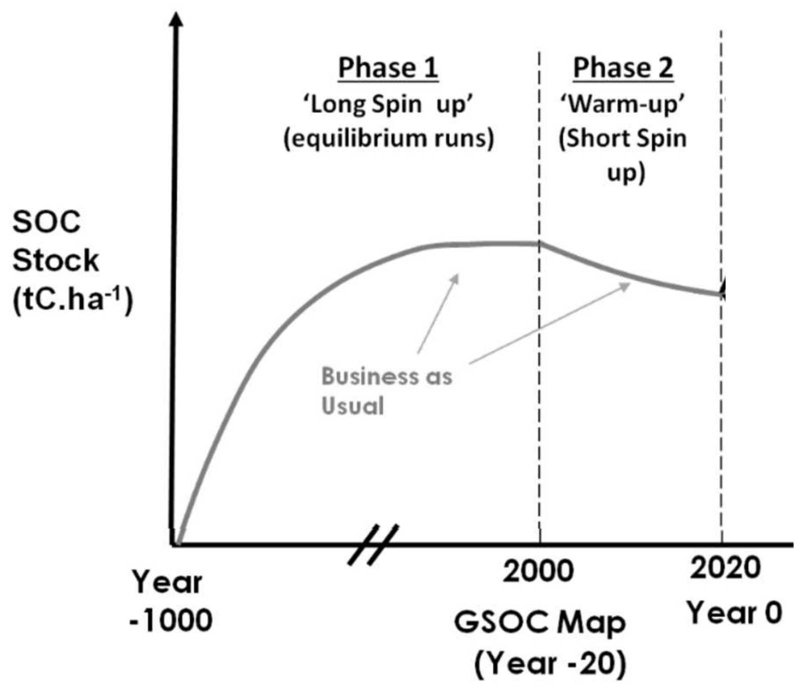

Modeling procedure

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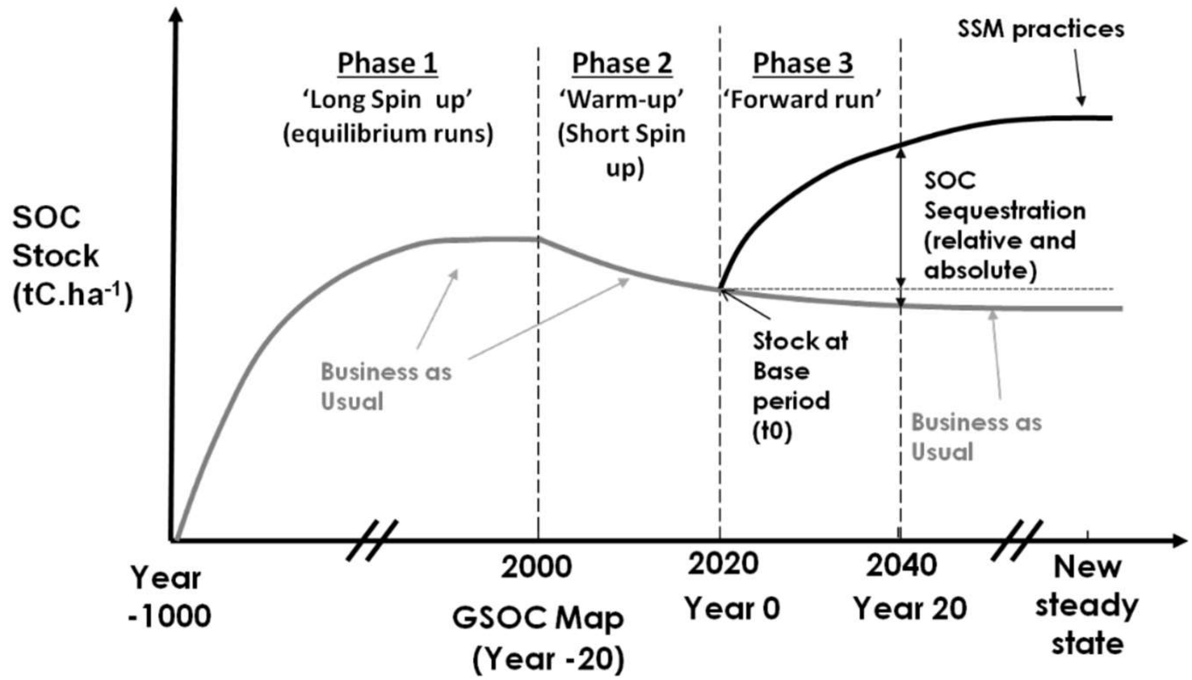

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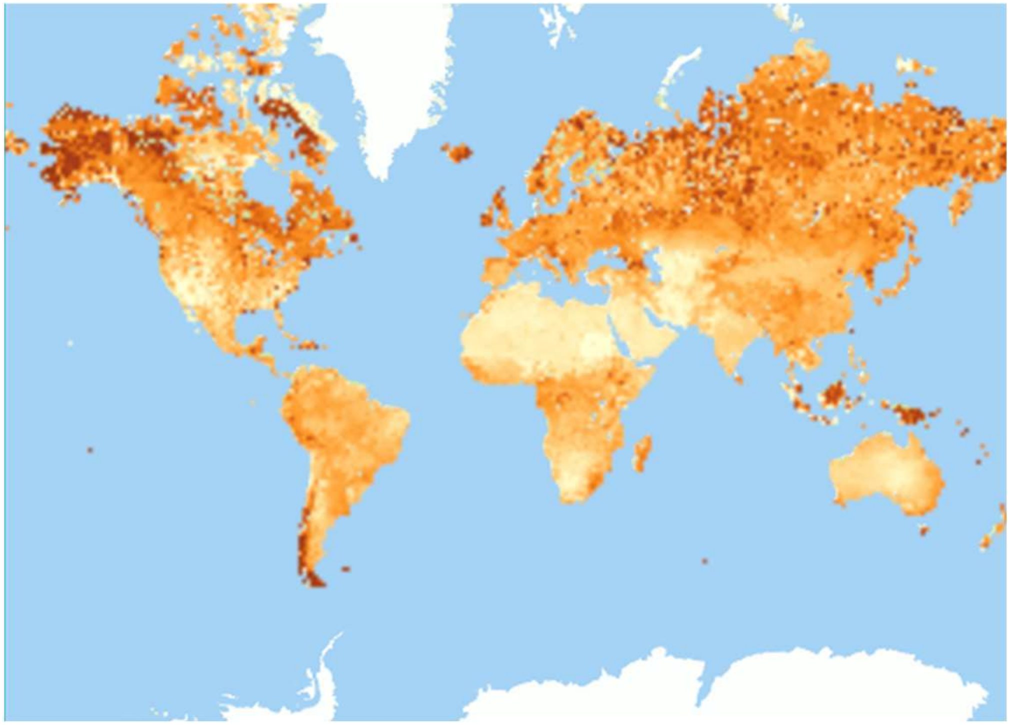

FAO, 2020

- WHAT ARE THE LIMITATIONS OF THIS CASE STUDY?
- CAN YOU IDENTIFY AN IMPORTANT MISSING STEP?

Key conclusions

Key conclusions

- **Select** a model adapted to the ecosystem you want to study

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- **Adapt** the model to your local conditions

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- **Evaluate** the performance of the model with observational data

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- Assess the **uncertainty** of the predictions, e.g., multi-model ensembles

Key conclusions

- **Select** a model adapted to the ecosystem you want to study
- **Adapt** the model to your local conditions
- Gather required **data** to implement the model
- **Evaluate** the performance of the model with observational data
- Assess the **uncertainty** of the predictions, e.g., multi-model ensembles

"Models are a way to increase the power of data"

Thank you for your attention!

bruni@geologie.ens.fr

Following:

Demonstration | Q&A

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