The stakes and challenges related to monitoring soil carbon stock changes: a focus on arable land

Eric Ceschia (INRAE/CESBIO)

With contributions from Ahmad Al Bitar, Taeken Wijmer, Ainhoa Ihasusta, Ludovic Arnaud, Rémy Fieuzal, Jean François Dejoux

FairCarbon, 25-27 November 2024, Sète (France)

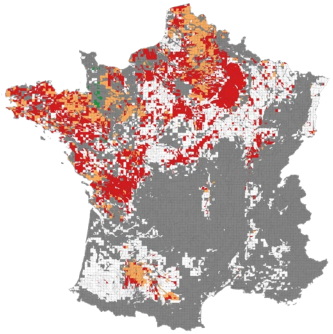
Increasing Soil Organic Carbon stocks, a climate and food security issue

Increasing SOC stocks in soils by 0.4% (or 4 per 1000) per year would offset global annual CO_2 emissions but it would also increase soil fertility and crop resilience to climatic extremes ➔ **but where and how ?**

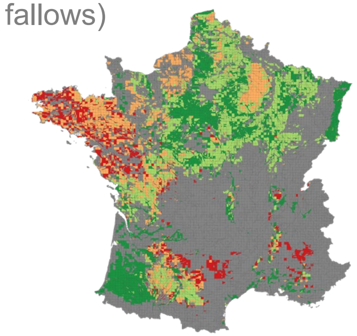
National expertise : Stocker du carbone dans les sols français. Quel potentiel et à quel coût ? (Pellerin et al. 2019) ➔ national statistics on practices (AGRESTE), STICS agronomic model with run over 1km grids, considering only the main crop rotations in a given grid + several scenarii (see Launay et al 2021b).

Percentage of intercrop periods with a cover crop during the crop rotation

In the baseline (current farming practices, mostly during winter)



In the scenario with expansion of cover crops (CC during winter and summer fallows)



2%-25%
25%-50%
50%-75%
75%-97%

Examples of cover crops

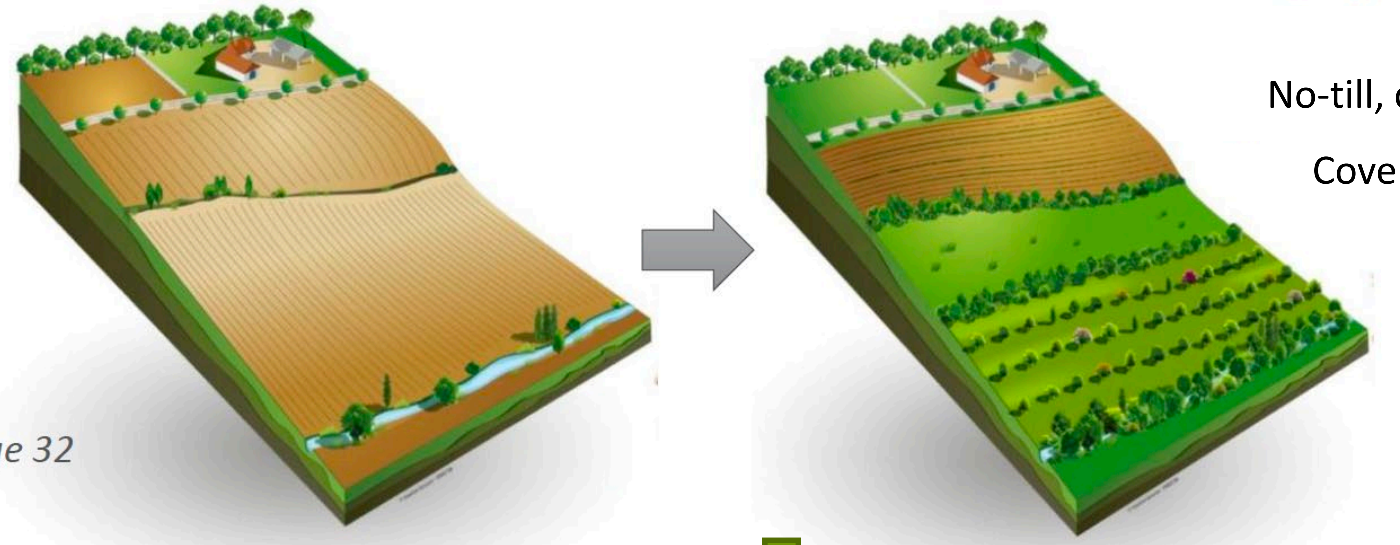
- Additional C storage potential of 5.78 Mt C/year in the 0-30 cm soil layer (approximately 8.6 Mt C/year if we consider no cover crops at all in the reference scenario)
- It represents an annual increase of:
  - +5,2 (to +8,3 %) of SOC stocks for the arable lands ➔ 62 % of this effect comes from the cover crops
  - +0,9 % for the grasslands

Reality is more complex

Level of adoption of Carbon farming practices ? Where ? ➔ No information at plot/farm scale

Conventional agriculture

Agro-ecological practices



Illustrations: Arbre et Paysage 32

No-till, crop diversification

Cover crops ➔ no info in the LPIS (RPG)

Straw management

C storage ?

How to assess the impacts of those practices in terms of CO_2 emissions/soil organic carbon (SOC) stock changes at the plot scale but over large areas?

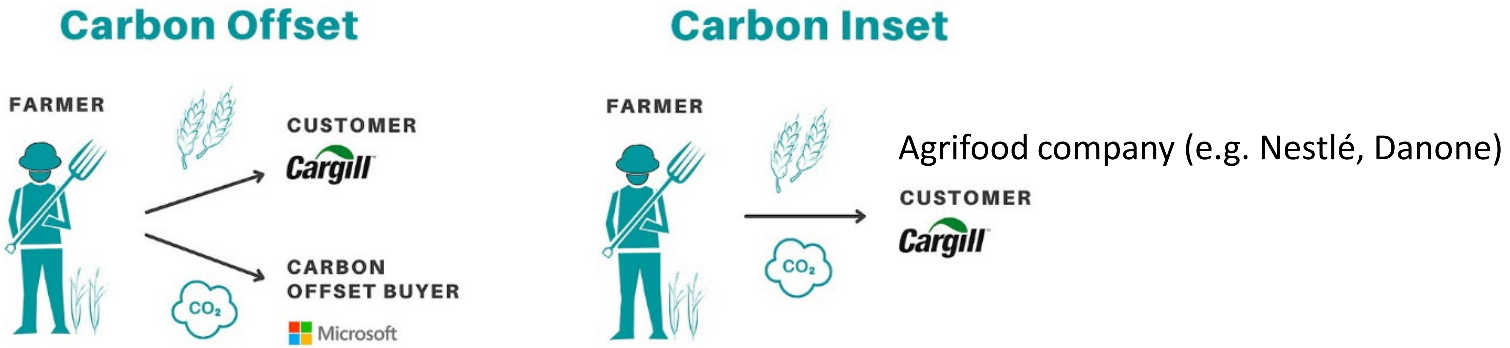
➔ Need for a new generation of tools providing an exhaustive/objective vision of the effect of management on SOC stock changes adapted to different contexts of application

Different context of MRV the SOC stock changes

MRV = Monitoring, Reporting and Verification

- National inventories; Nationally Determined Contributions (NDCs) under the Paris agreement,

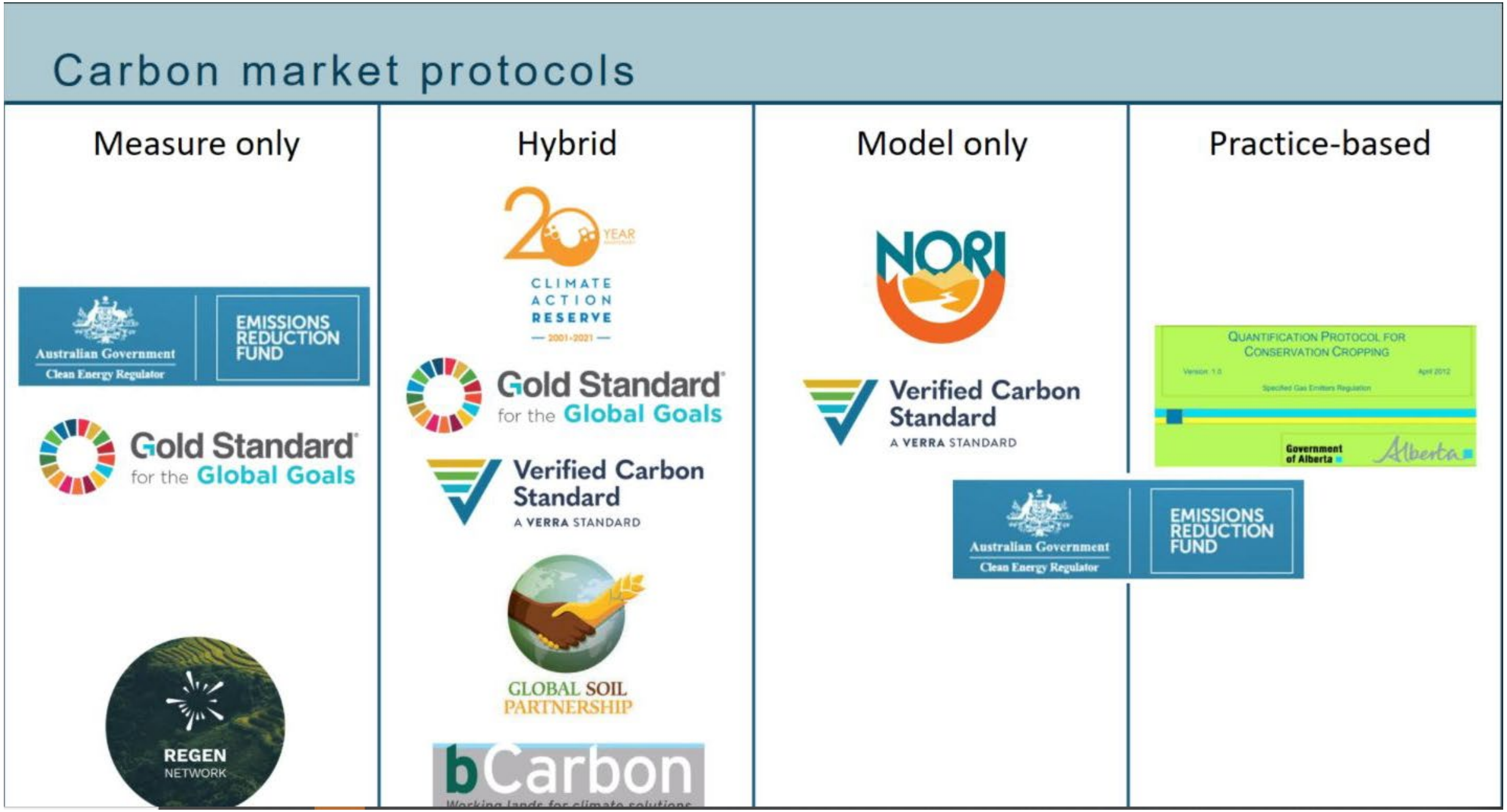
- Carbon offset programs (Voluntary Carbon market) mainly on forest up to now but growing fast for cropland (e.g. LABEL BAS CARBONE), and recently insetting programs are developing too,



- Common Agricultural Policy? ➔ operational methods are still missing

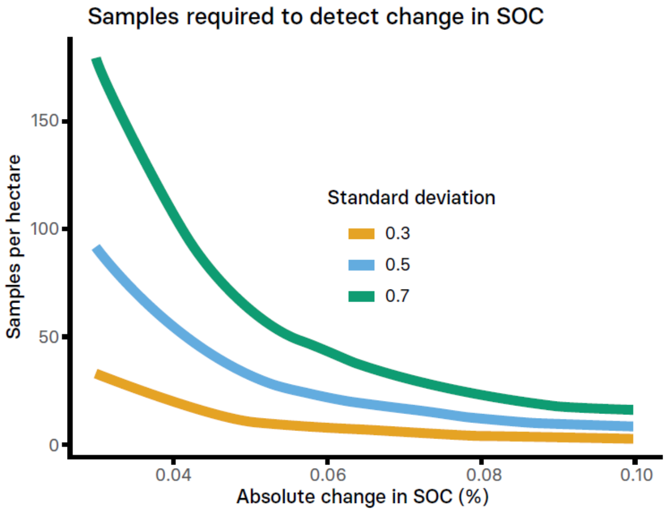
Each context of application has its specificities, requirements & rules

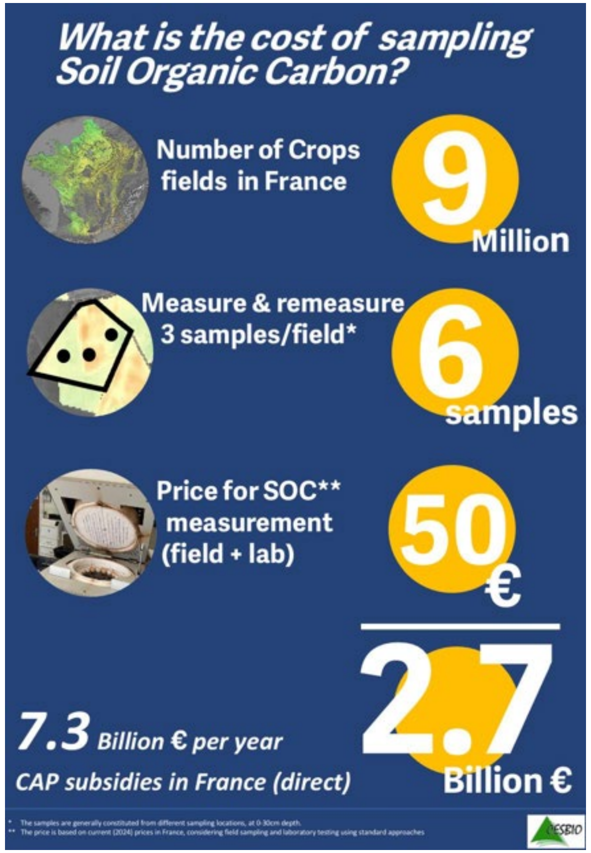
Some of the methods/protocols used for the VCM



How to Monitor SOC stock changes ?

- Measure & re-measure of soil SOC content/bulk density ➔ VCM, NDCs 





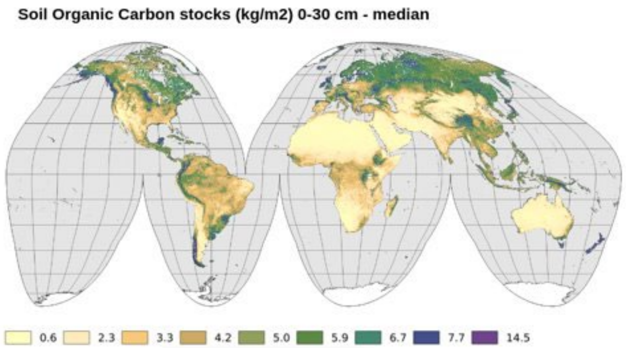
Large scale implementation for the VCM would require a large number of samples for measure and re-measure ➔ very expensive, high uncertainty, risk of unrepresentative sampling (can be reduced by mapping soil properties ➔ stratified sampling), depth issue… ➔ new methods (NIRS, gamma ray) may solve some of those issues

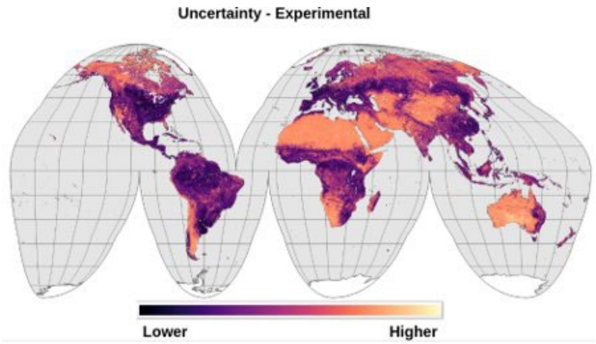
A. Al Bitar

How to Monitor SOC stock changes ?

- Measure & re-measure of soil SOC content/bulk density ➔ VCM, NDCs 

- Statistical models spatialising in situ soil data using related patterns (e.g. Szatmári et al. 2021) and digital soil mapping (e.g. Heuvelink et al., 2020) ➔ NDCs, global products





SoilGrids 2.0

How to Monitor SOC stock changes ?

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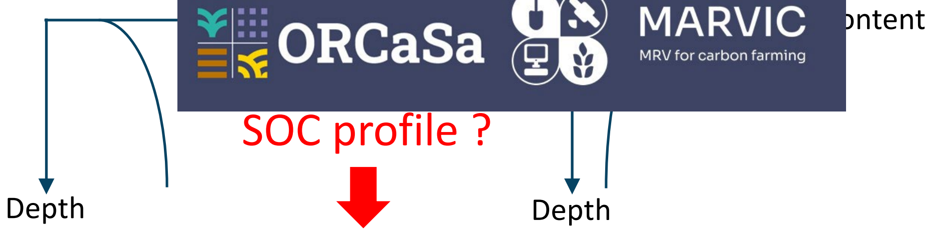
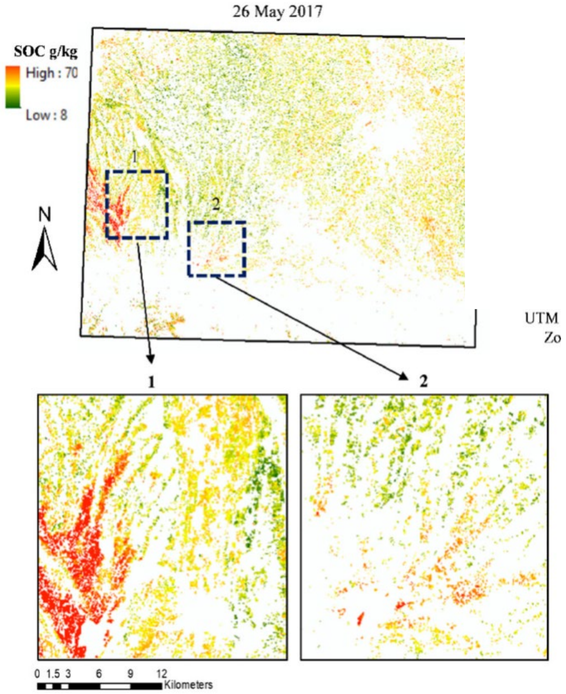
- TIER 1 & 2: estimated standard values for Specific Land Management measures (activity X leads to increase/decrease in SOC) ➔ only for NDCs,
- ~~Monitoring of SOC stock directly from remote sensing ?~~



ORCaSa MARVIC MRV for carbon farming

SOC profile ?

SOC stock ?



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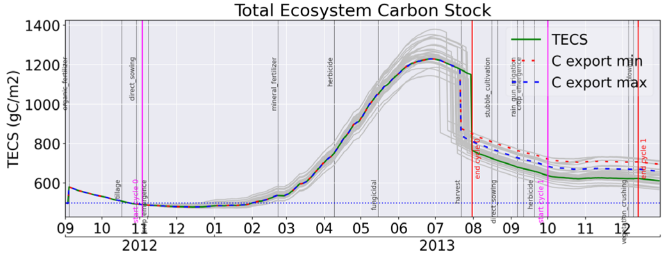
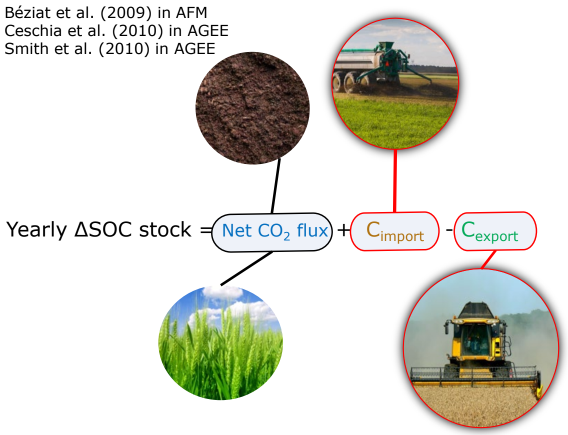
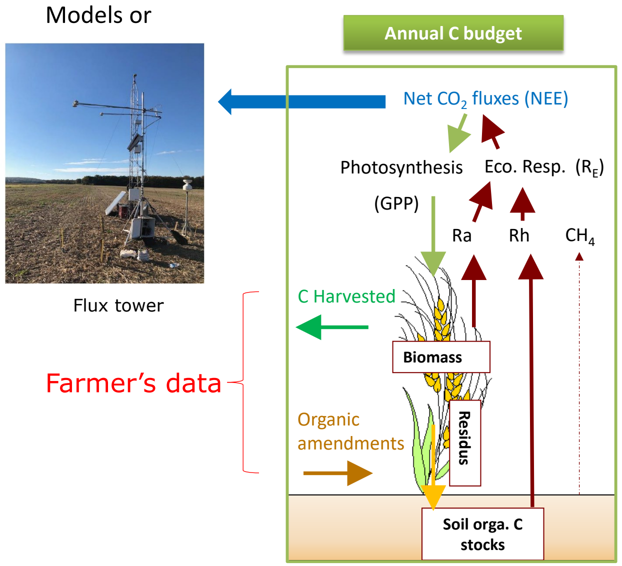


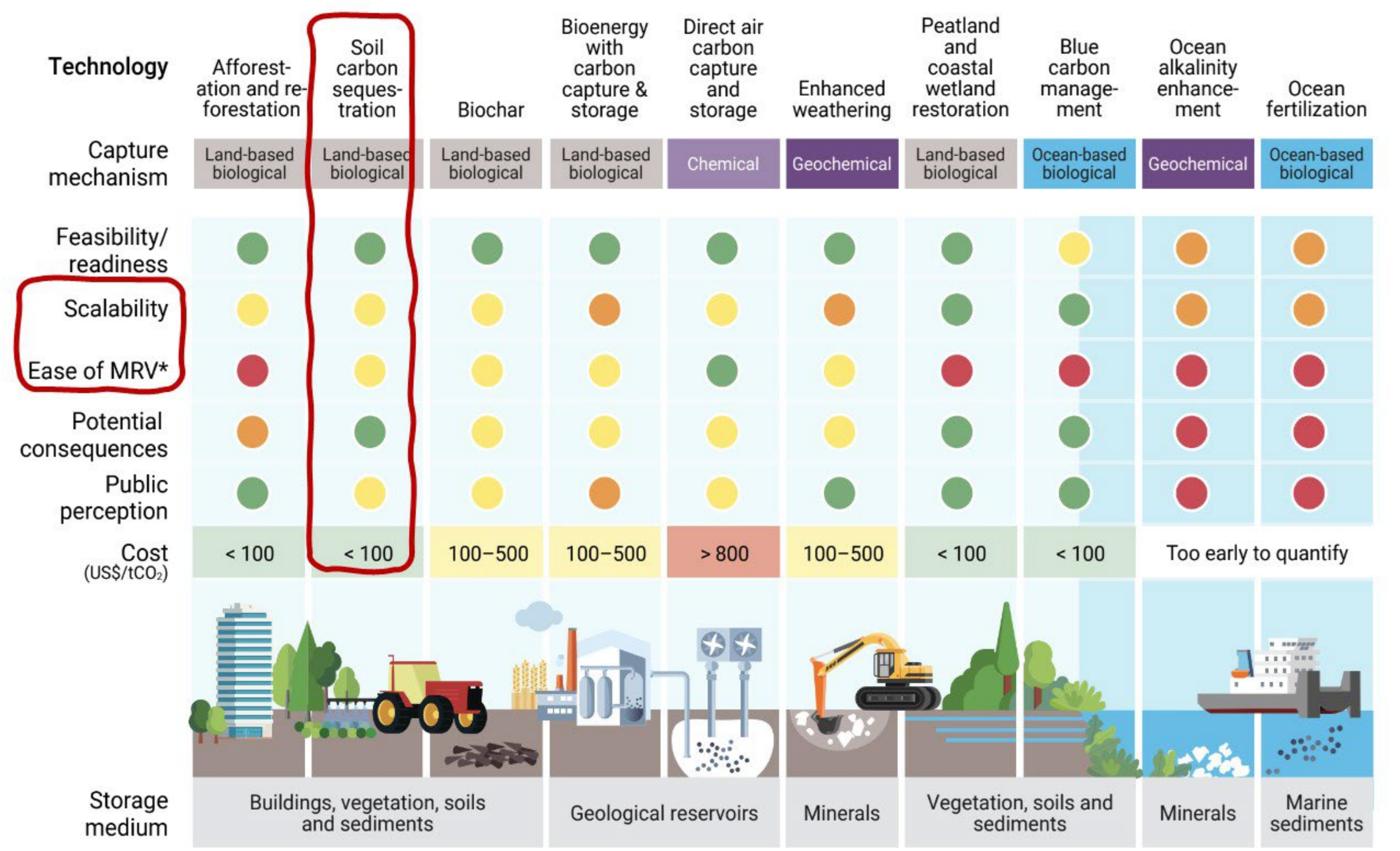




Monitoring of SOC is an ecosystem issue !!! ➔ C budget approach
Yet the methodology to be implemented will depend on the context, availability/accuracy of data, cost/accuracy issues

The challenges of monitoring SOC stock changes

Need for scalable, multi-context (NDC, CAP, VCM, insetting), automatized, cheep, reliable, transparent method



Sources: UNEP - Emissions Gap Report (2023), Adapted from Geden et al. (2022) and Pisciotta, Davids and Wilcox (2022).

The challenges of monitoring SOC stock changes

Need for scalable, multi-context (NDC, CAP, VCM, insetting), automatized, cheep, reliable, transparent method

Following as much as possible CIRCASA's recommendations (see Deliverable 3.1):

- Modular & transparent approach with uncertainty assessment on SOC stocks,
- Several soil models instead of one ➔ allowing ensemble approach,
- Assessment of the different components of the C budget in the development/verification process,
- Relying on strong data infrastructures following the FAIR principles: e.g. Copernicus, ICOS (flux towers)…
- High resolution, relying on remote sensing (e.g. Sentinel 2) to quantify biomass production & restitution to the soil,
- …

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- …

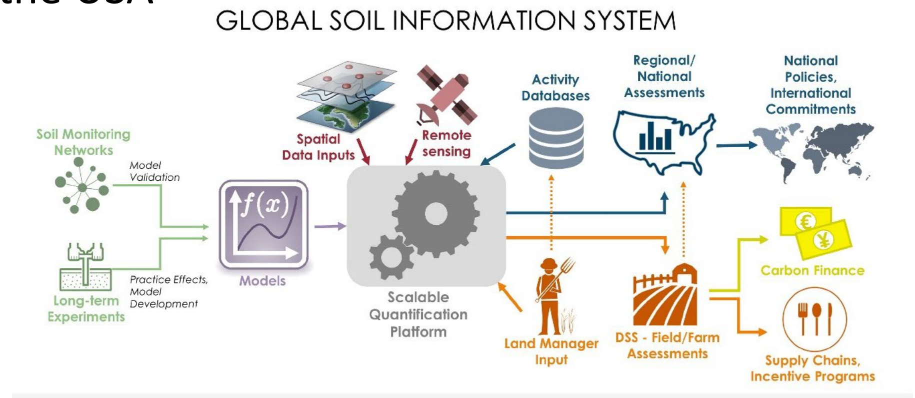
An compliant with the EU Carbon Removals and Carbon Farming Regulation in terms of baselines, assessment at plot scale, practices accounted for, uncertainty assessment…

➔ QU.A.L.ITY criteria

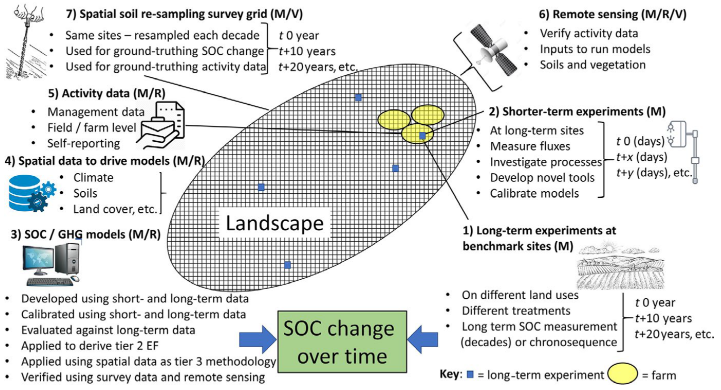
MRV frameworks for cropland SOC stock changes

Conceptual

Paustian et al. (2019): NDC, C market in the USA

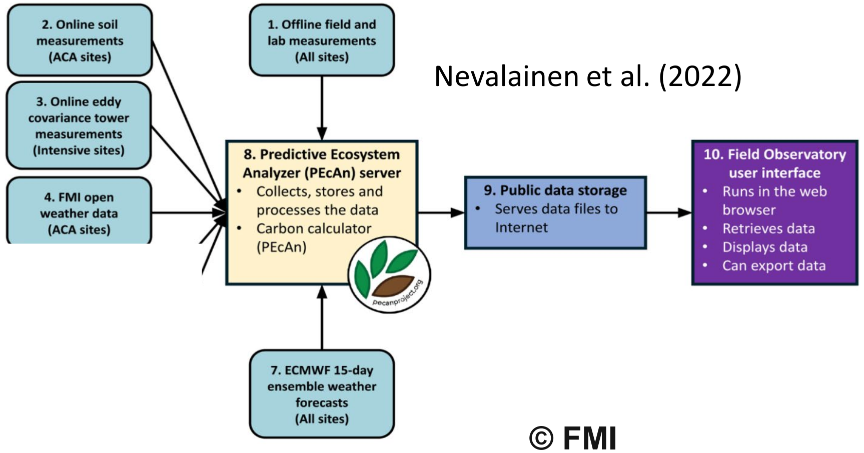


Smith et al. (2020)



Prototypes of Scalable Quantification plateforms

Field observatory network



Nevalainen et al. (2022)

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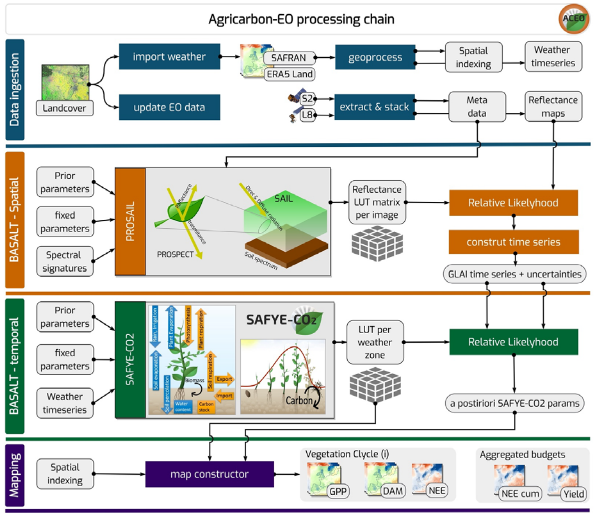
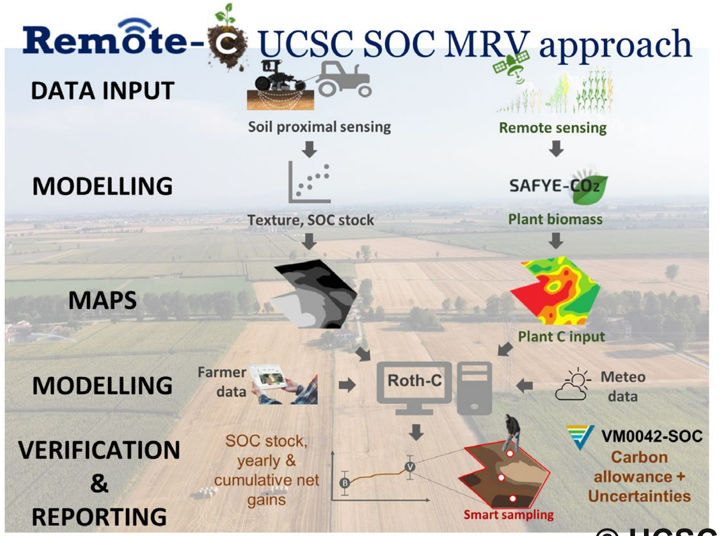


Wijmer et al. (2024) © INRAE/CESBIO



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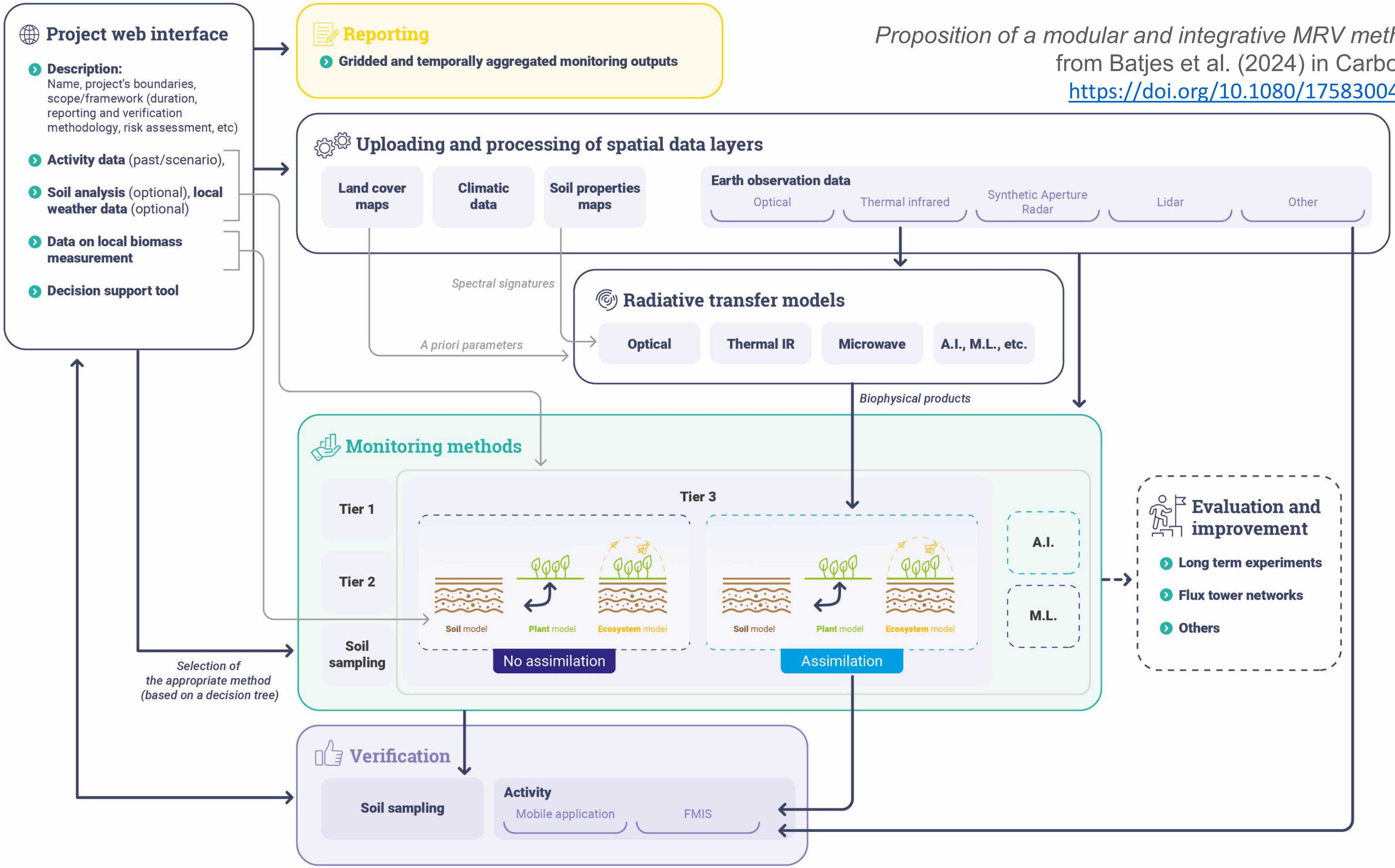
Modular and harmonized MRV framework for cropland SOC stock changes: focusing on the Monitoring component

Proposition of a modular and integrative MRV methodology for SOC stock changes
from Batjes et al. (2024) in Carbon management
https://doi.org/10.1080/17583004.2024.2410812.



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Because soil carbon matters

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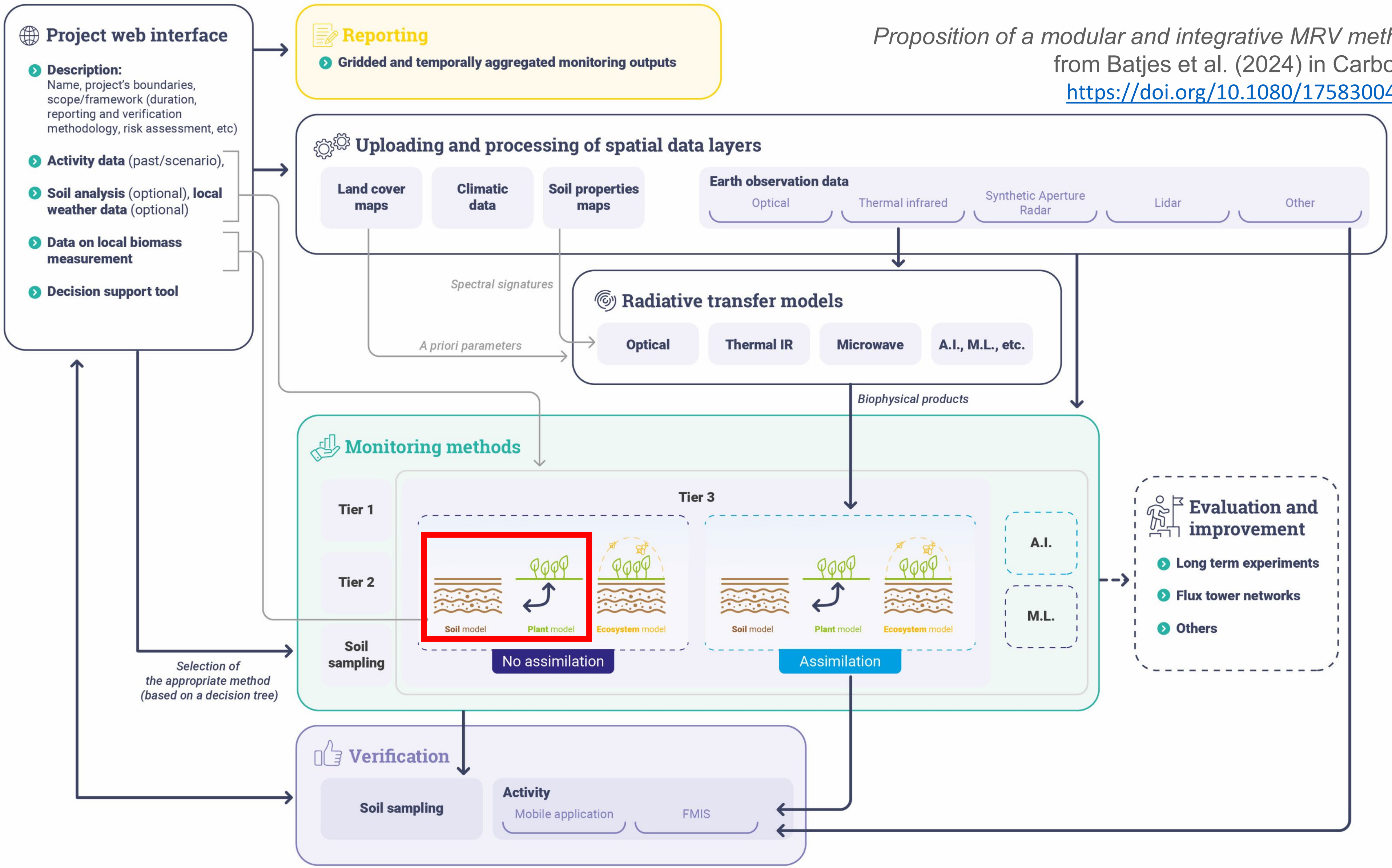

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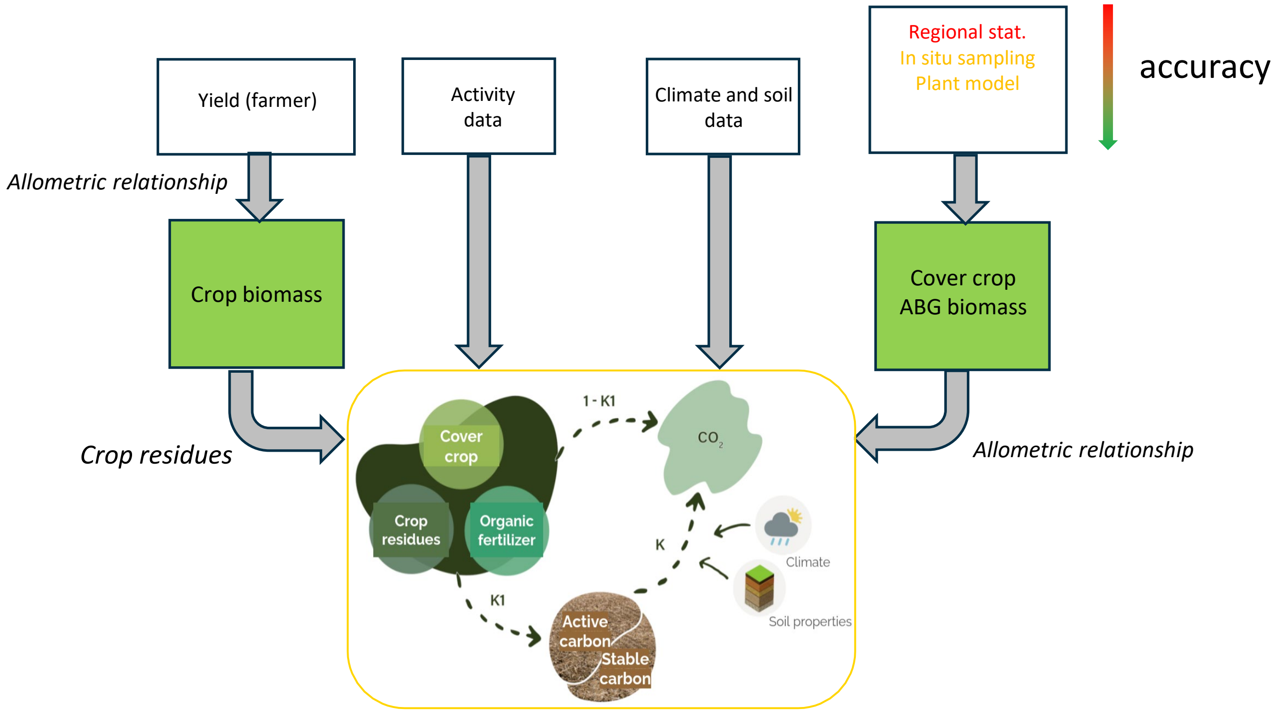
Soil centered approaches for SOC monitoring

e.g. AMG ➔ LABEL BAS CARBONE



AMG soil model (Clivot et al 2019)

Soil centered approaches for SOC monitoring

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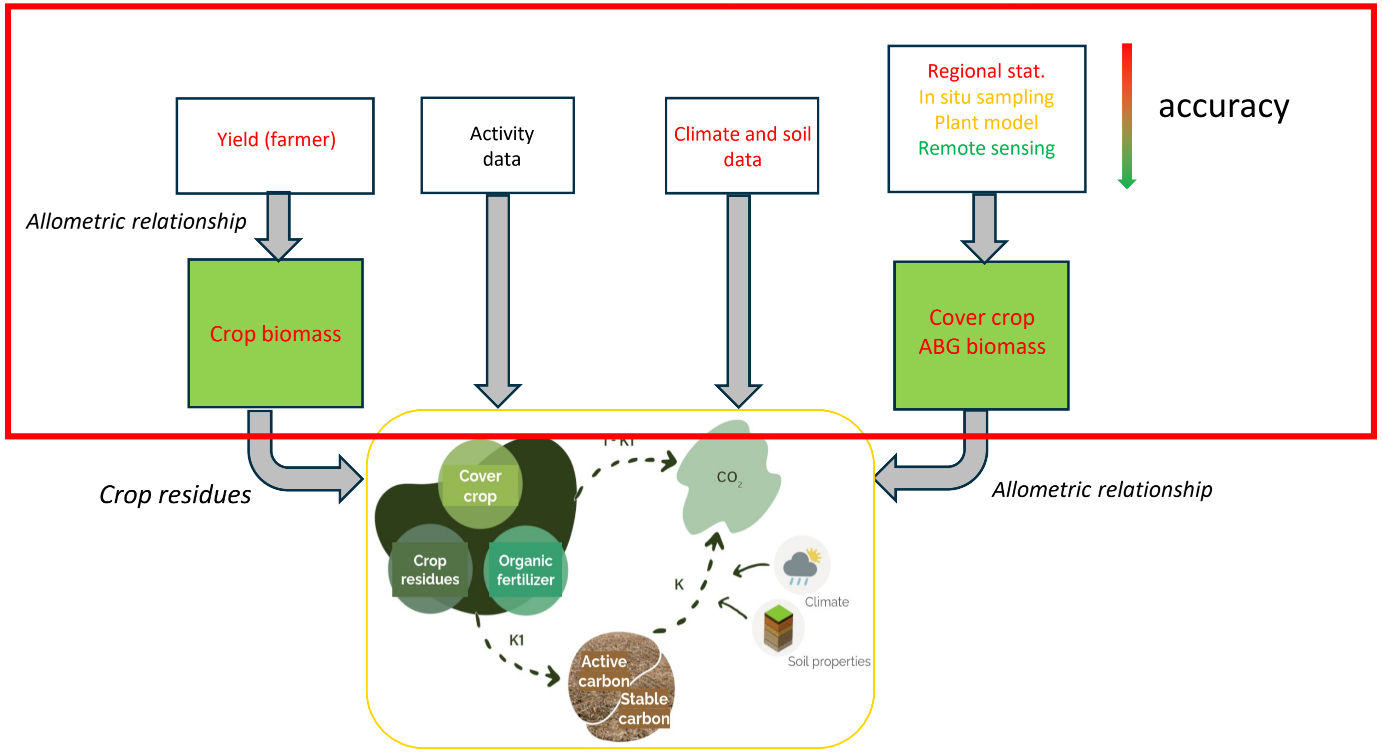
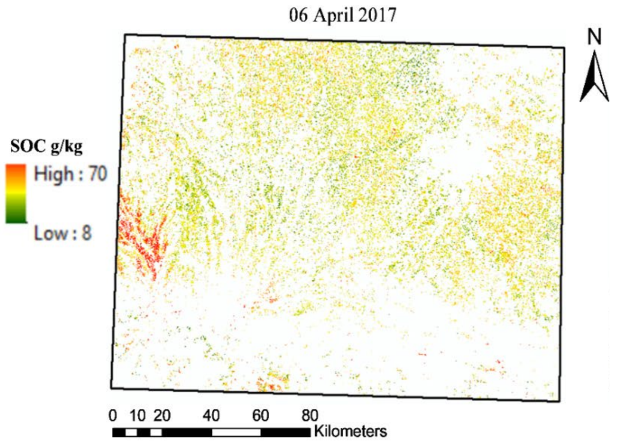


AMG soil model (Clivot et al 2019)

Strong spatial variability !!

Example of spatial variability in superficial SOC content

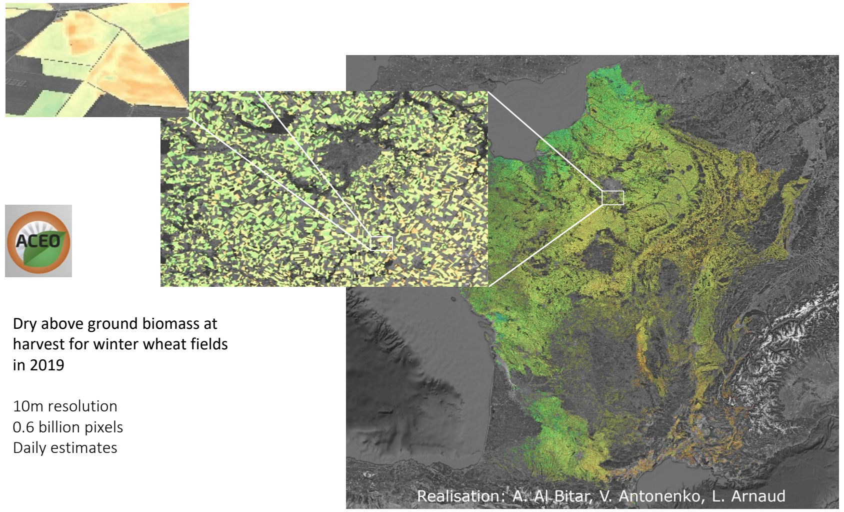
Urbina Salazar et al. (2021)



Spatial variability in aboveground biomass, yield and C inputs

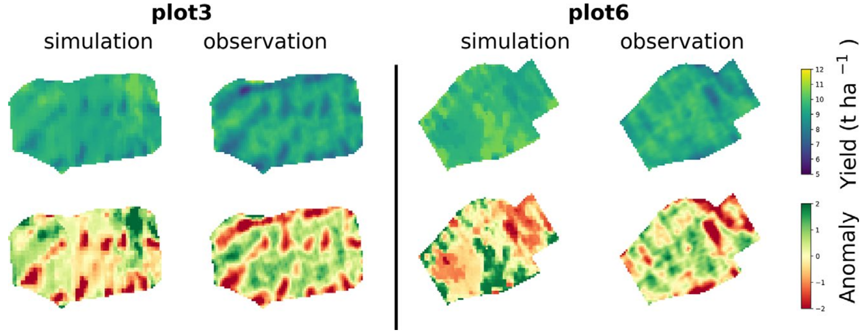
CROPS

Intra and inter plot spatial variability in straw cereal ABG biomass in France (2019)



Wijmer et al (2024)

Spatial variability in wheat yield in France (2019)



Both are wheat !!!!

Harvest index (Yield/aboveground biomass) varies from 0.3 to 0.6 for wheat (Dai et al 2016 : https://doi.org/10.1016/j.biombioe.2015.12.023)

➔ **not an accurate approach to estimate ABG biomass and crop C input to the soil based on farmer's yield data !!!**

Spatial variability in aboveground biomass, yield and C inputs

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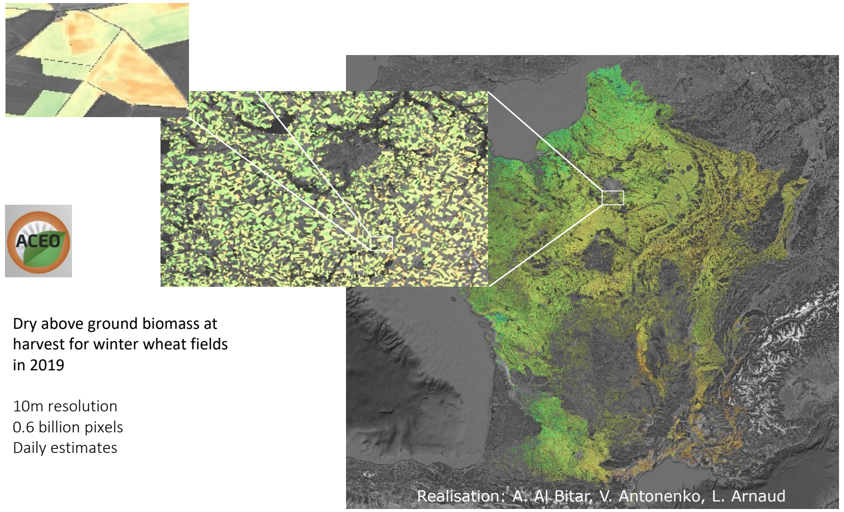
Intra and inter plot spatial variability in straw cereal ABG biomass in France (2019)

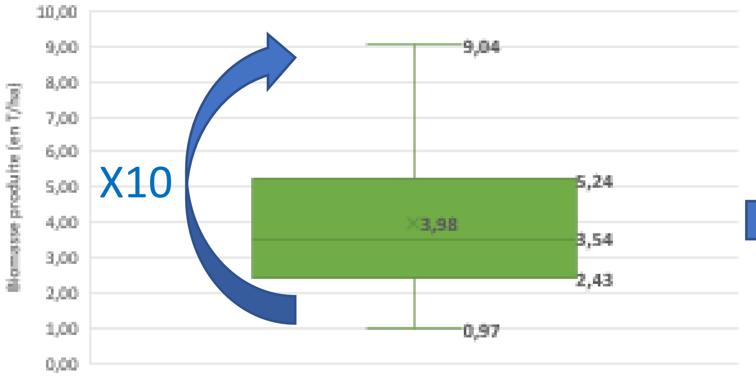


Dry above ground biomass at harvest for winter wheat fields in 2019

10m resolution
0.6 billion pixels
Daily estimates

COVER CROPS

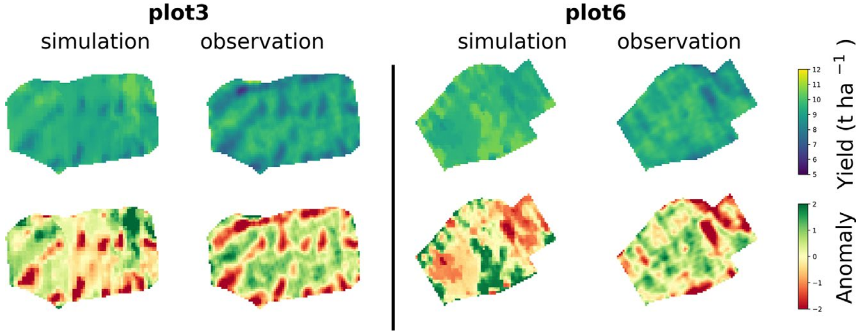
Variability in fava bean cover crop biomass at the Nataïs producer network in 2019



Field workers were asked to collect 2m^2 of biomass samples that they considered to be representative of the plot (source: Agrod'OC)

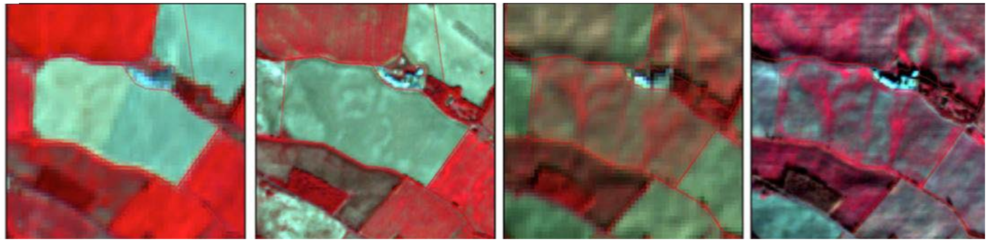
- Strong inter & intra plot spatial variability of biomass inputs to the soil not currently accounted for by most MRV approaches
- EO based approach are needed to better account for those effects !!!

Spatial variability in wheat yield in France (2019)



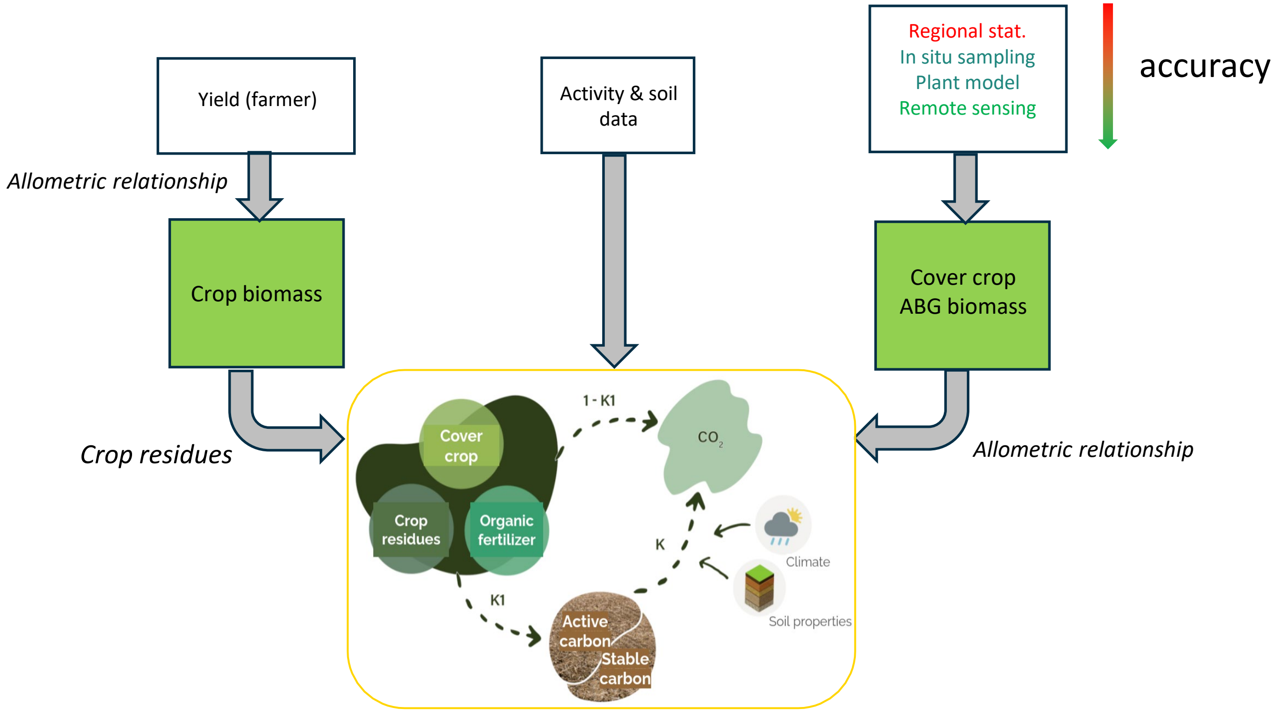
Data SPOT4/5

18/07/2012 06/09/2012 15/11/2012 29/12/2012



Soil centered approaches for SOC monitoring

e.g. AMG ➔ LABEL BAS CARBONE



AMG soil model (Clivot et al 2019)

- 🙂 **You can do MRV with only a soil model (simple approach…)**
- 🙂 **Most crops & carbon farming practices**
- **Cropping systems of the farm (not plot level)**
- **Cost varies if initial soil sampling done or not (not mandatory) and if automatised access to activity data through FMIS**
- 🙁 **Uncertainty assessment**
- 🙁 **Scalability**
- **Accuracy (because of the spatial variability in biomass and soil properties data used as input for the soil model)**
- 🙁 **No verification with measure-remeasure**

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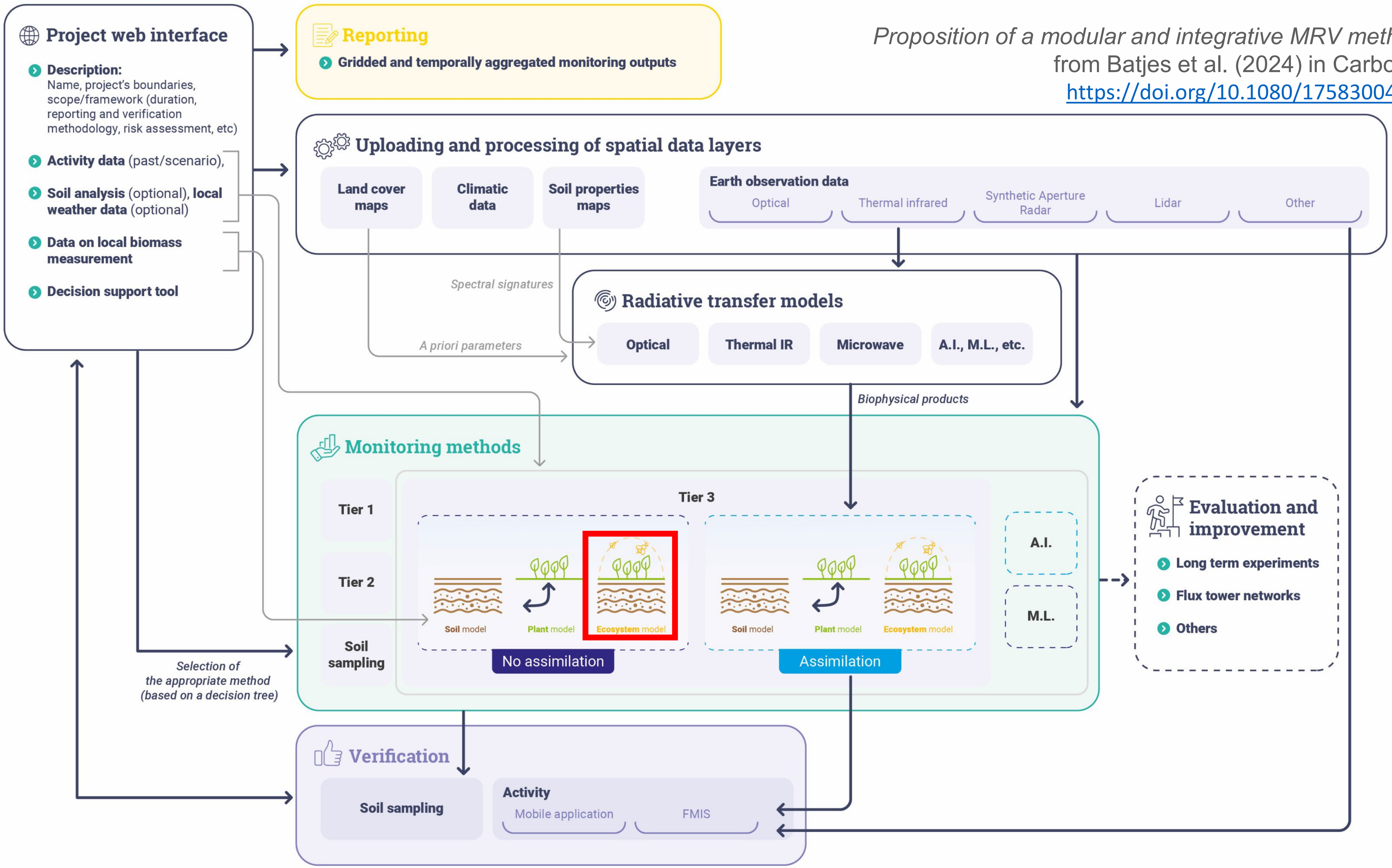

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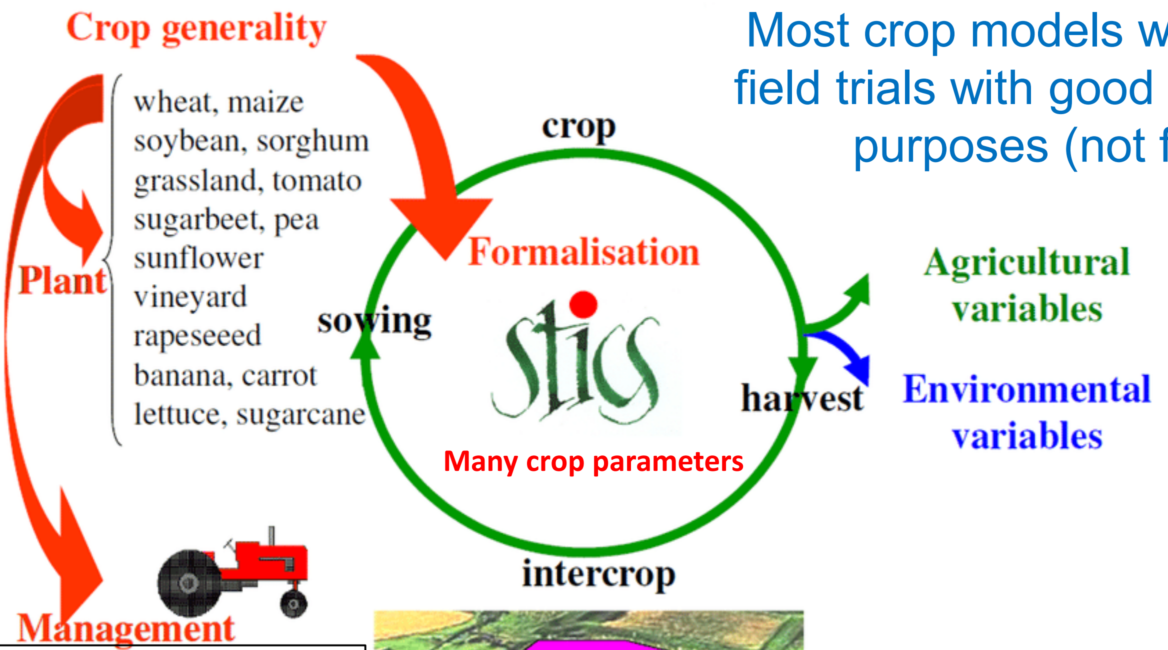
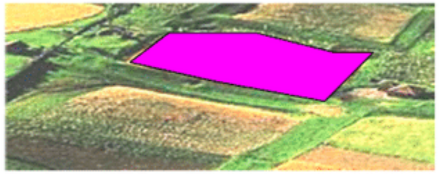
Ecosystem modelling approach for SOC monitoring

Input data

- Practices:
  - Crop rotation,
  - seeding data/density
  - Mineral fertilisers
  - organic amendments
  - irrigation…
- Climatic data
- Soil properties (texture, MO content, etc.)



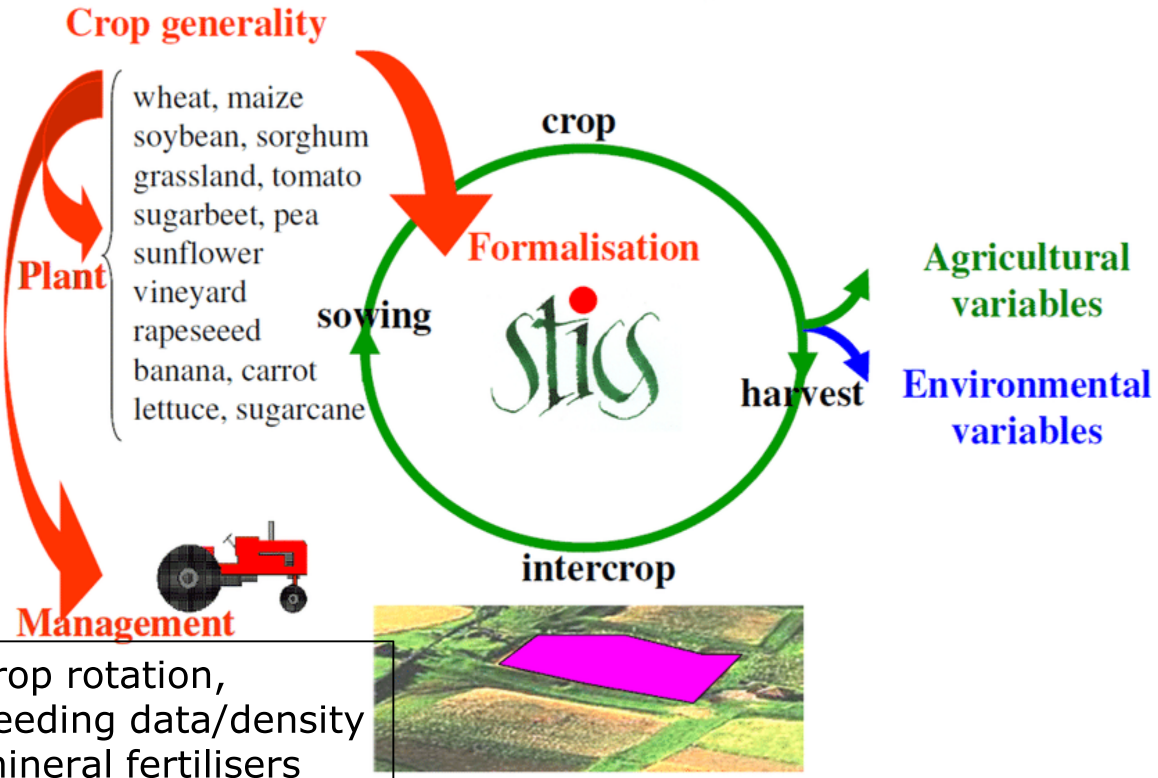
- crop rotation,
- seeding data/density
- mineral fertilisers
- organic amendments
- irrigation
- …



Most crop models were calibrated/validated on field trials with good deep soils and for research purposes (not for operationnal MRV)

A lot of parameters and input data needed (activity data…), issue concerning spatial variability of soil properties, no accounting for damages caused by pest/ deseases…lack of representation of biomass spatial variabity and of soil processes ➔ consequences for verification (where to sample? How many? Cost !!!)

Ecosystem modelling approaches for SOC monitoring



- crop rotation,
- seeding data/density
- mineral fertilisers
- organic amendments
- irrigation
- …

Good expertise in agronomical modelling needed

Most crops & carbon farming practices

Cost varies if initial soil sampling needed and access to activity data through FMIS

Uncertainty assessment

Scalability (many parameters and activity data…)

Lack of objective assessment of crop development (no accounting for pest, cropping accident

Accuracy depends on access or not to local soil data and to accuracy of activity data

Verification requires many samples

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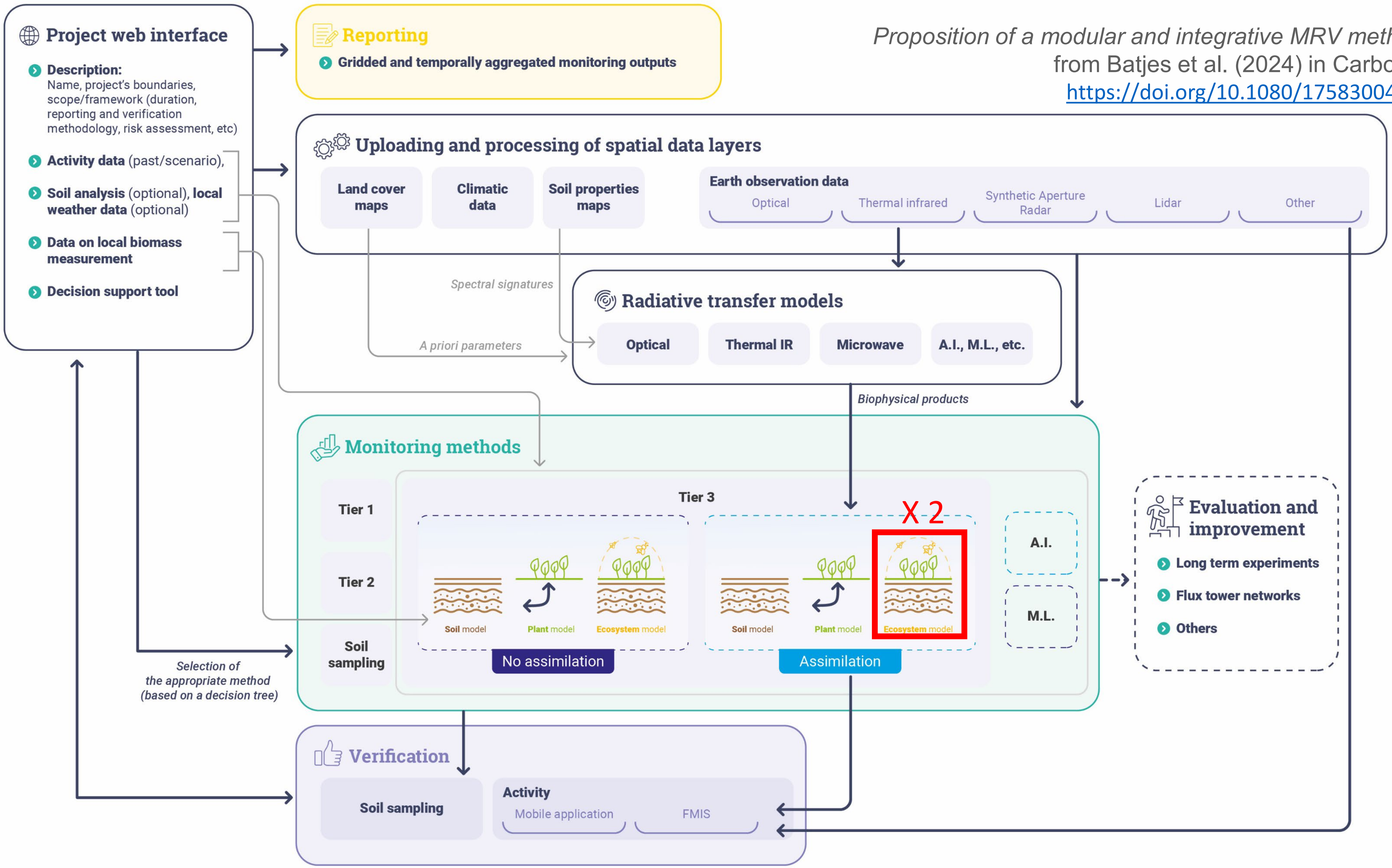

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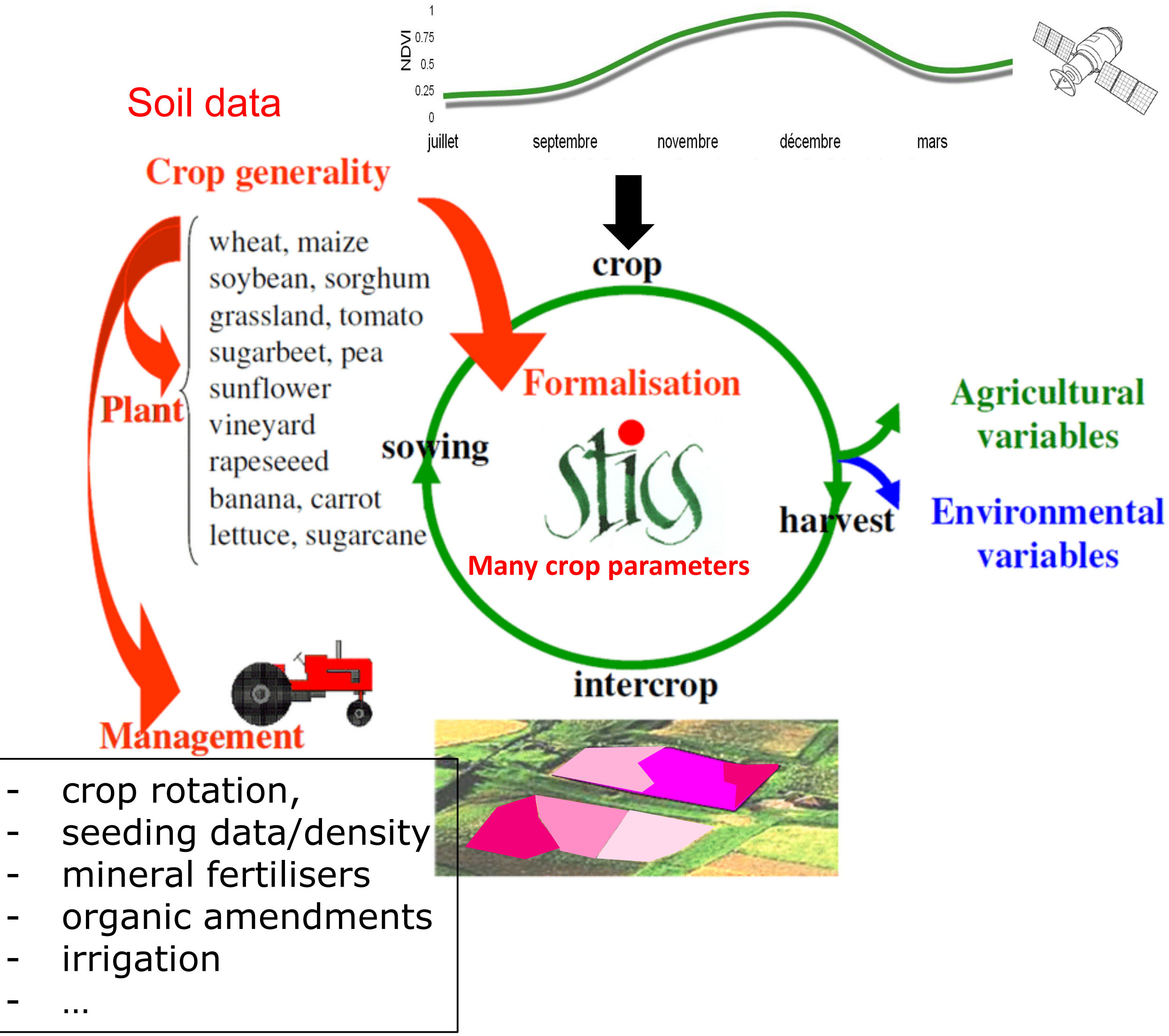
Ecosystem modelling approach with EO assimilation for SOC monitoring



Good expertise in agronomical modelling needed

Most crops & carbon farming practices

Cost varies if initial soil sampling needed and access to activity data through FMIS

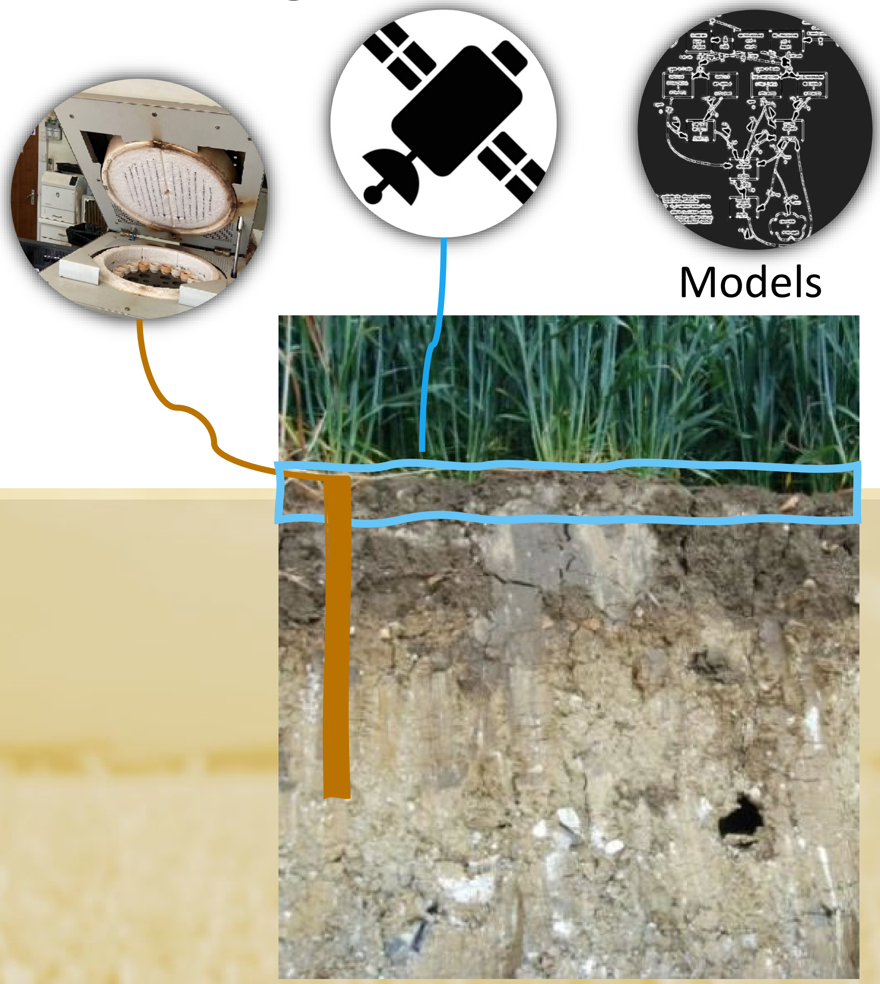
Uncertainty assessment

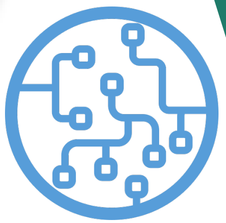
Scalability (many parameters, activity data…)

Better assessment of crop development

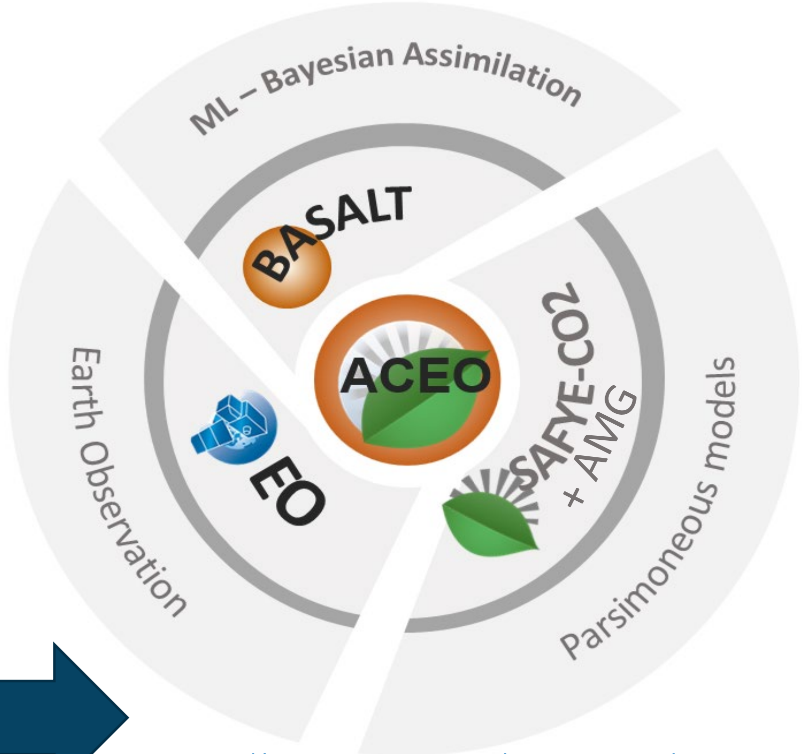
Accuracy depends on access or not to 1) local soil data, 2) accuracy of activity data and 3) access to operational EO observations

Limits of current methods for monitoring soil carbon





AI



https://www.cesbio.cnrs.fr/agricarboneo/agricarbon-eo/

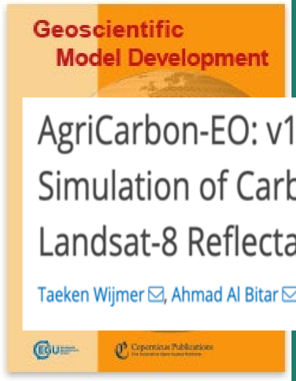
AgriCarbon-EO

A hybrid method combining **parcimonious process based ecosystem model**, remote sensing data assimilation and Machin Learning + In-situ data for cal/val

➔ Strong focus on assessing the effect of biomass input to the soil on SOC stock changes

The AgriCarbon-EO processing chain

A pre-operational multi-context end-to-end processing chain.

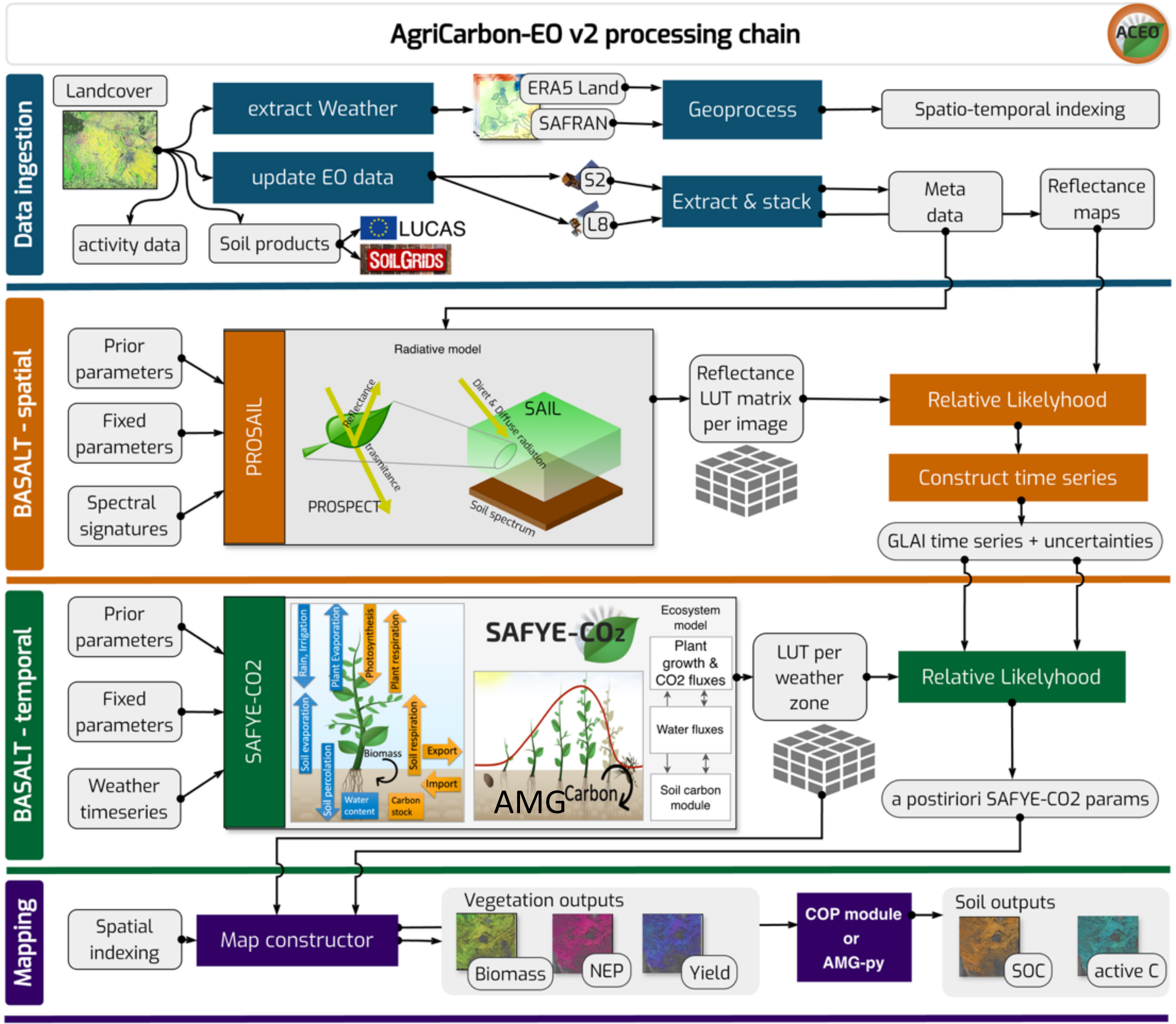


Wijmer et al. (2024)

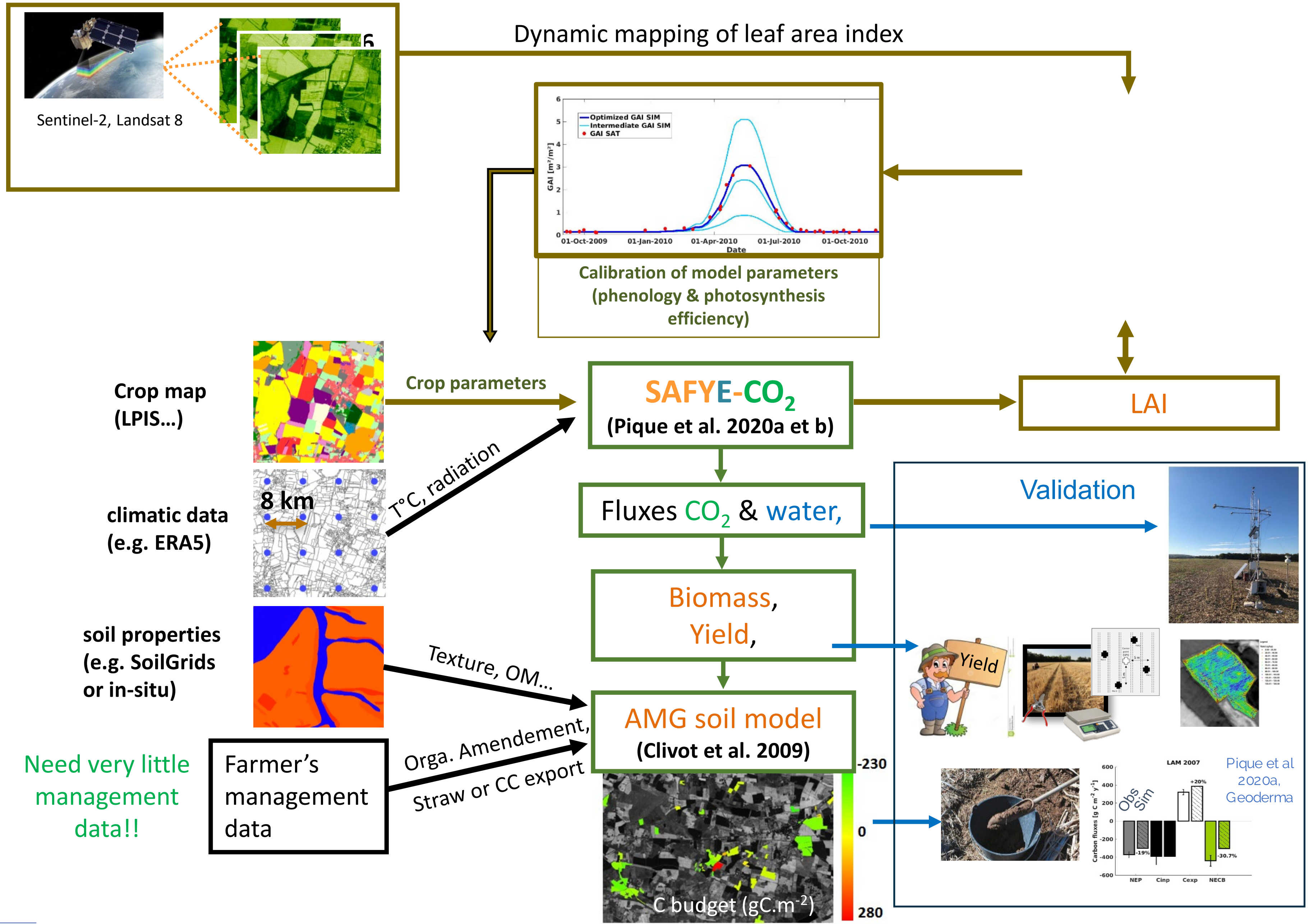
AgriCarbon-EO: v1.0.1: Large Scale and High Resolution Simulation of Carbon Fluxes by Assimilation of Sentinel-2 and Landsat-8 Reflectances using a Bayesian approach

Taeken Wijmer, Ahmad Al Bitar, Ludovic Arnaud, Rémy Fieuzal, and Eric Ceschia

Agri sector:



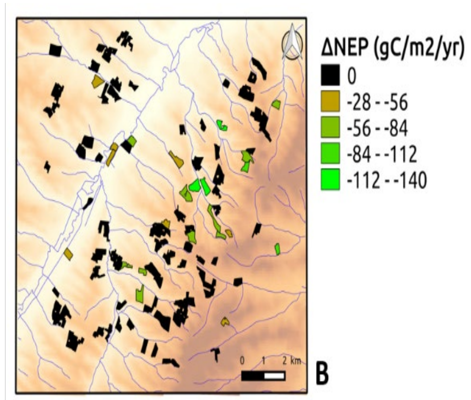
The SAFYE-CO2 model



Started 10 years ago

Objective : To force the crop model (SAFYE-CO2) to reproduce at plot level the dynamics and development intensity of the crop/cover crops as seen by satellite ➔ more precise and objective biomass estimates, implicit consideration of stress (N, water, etc.) and of some practices.

Automatic detection of cover crops, spontaneous regrowth /weeds and their impact on CO_2 fluxes/SOC ➔ only possible with remote sensing

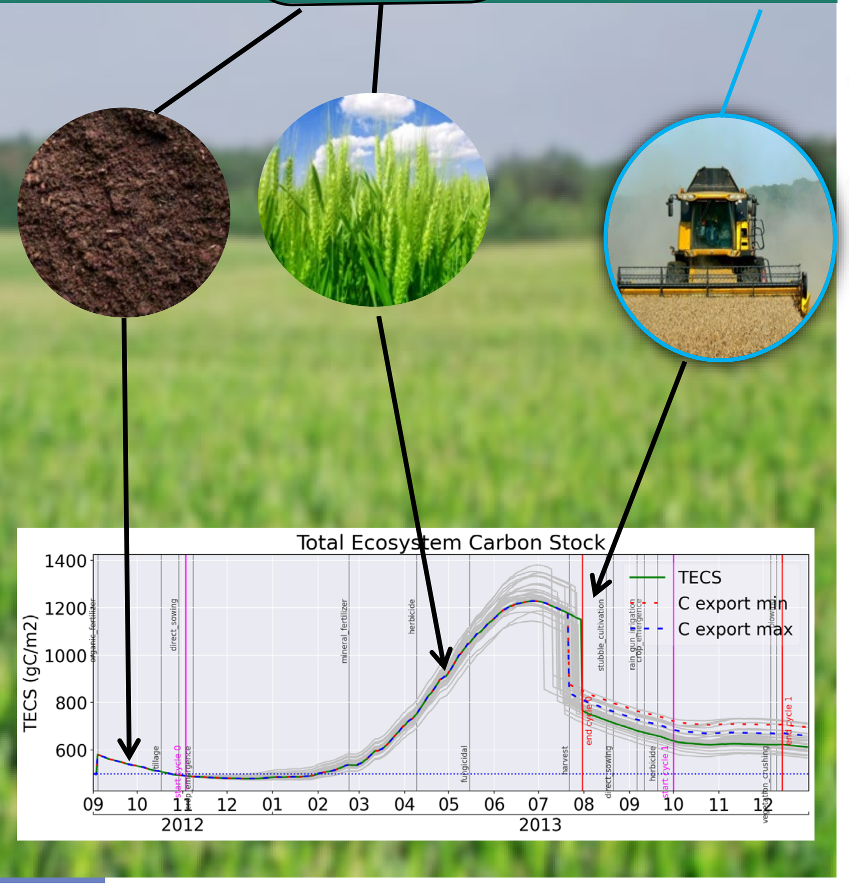


Pique et al (2020c) https://doi.org/10.3390/ecas2020-08141

Activity data provided by the farmer

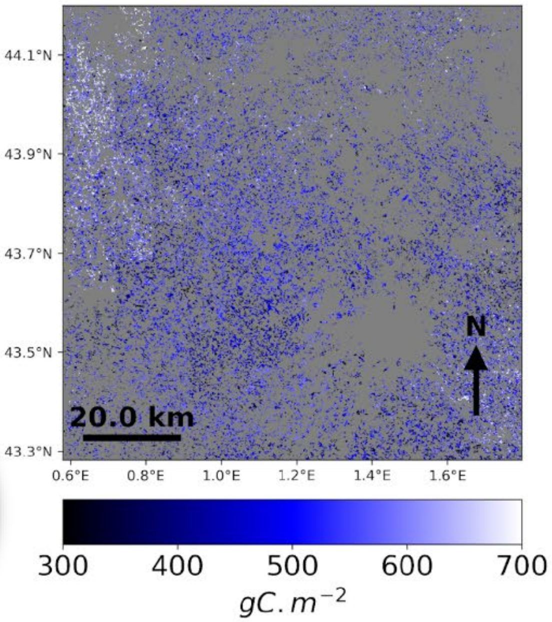
Annual carbon budget components

$$\Delta SOCstock = \text{Net } CO_2 \text{ flux} + C_{import} - C_{export}$$

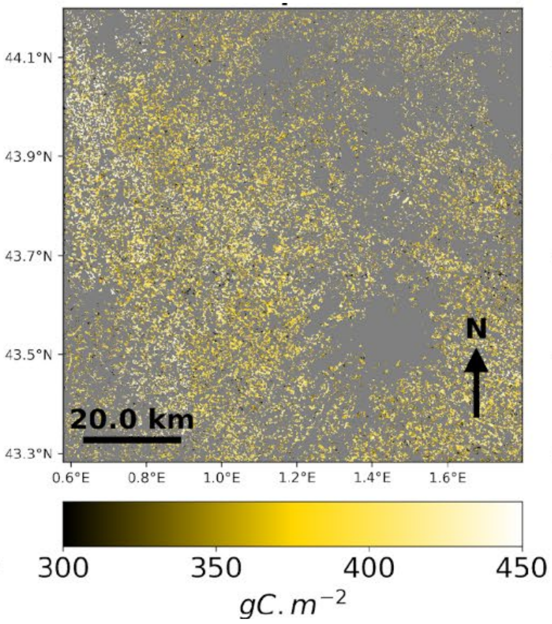


Straw cereals near Toulouse in 2019:
scenario with straw restitution and no organic amendment

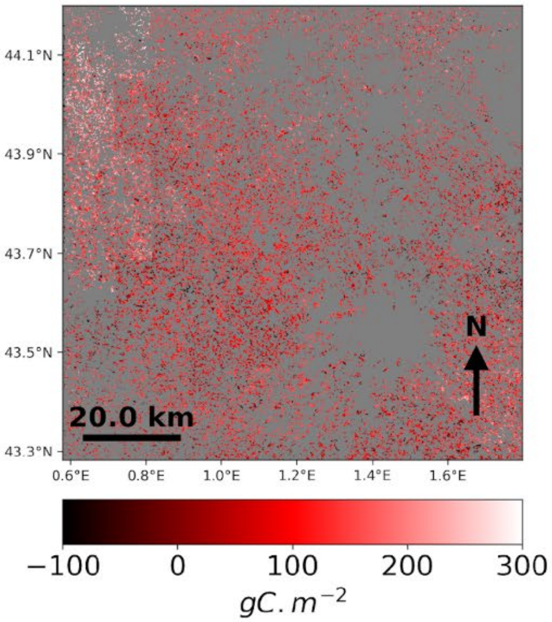
Net annual CO_2 flux (NEP)



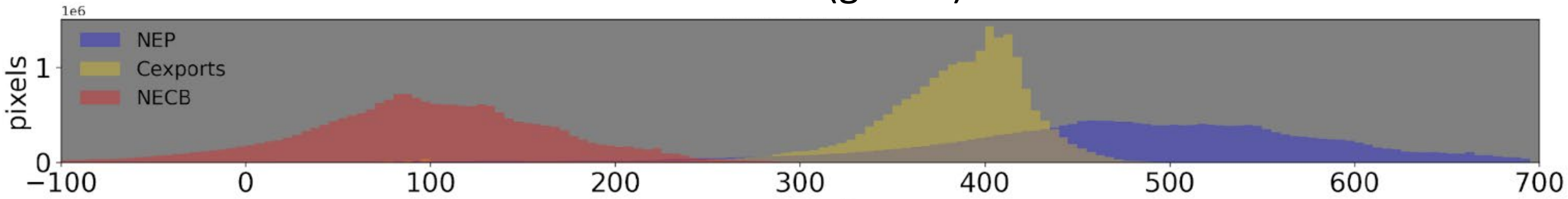
C exported at harvest



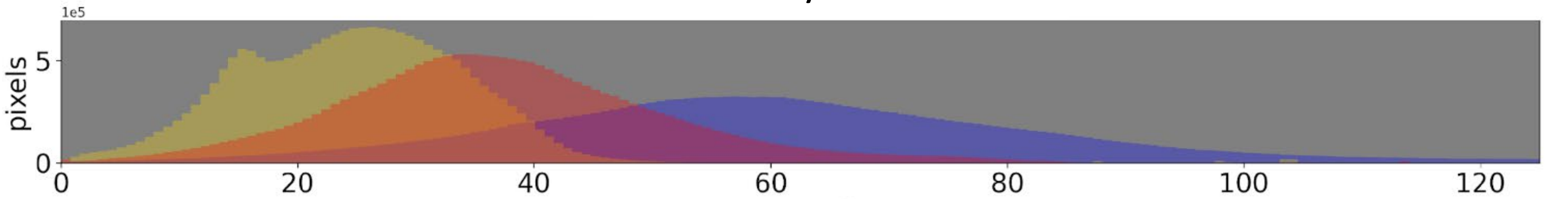
Annual C budget (NECB)



Mean value ($gC.m^{-2}$)

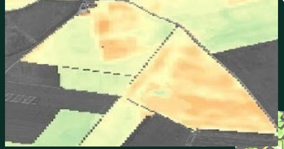


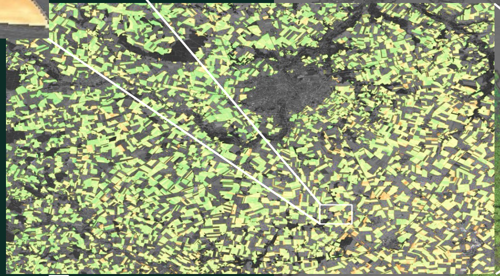
Uncertainty estimates



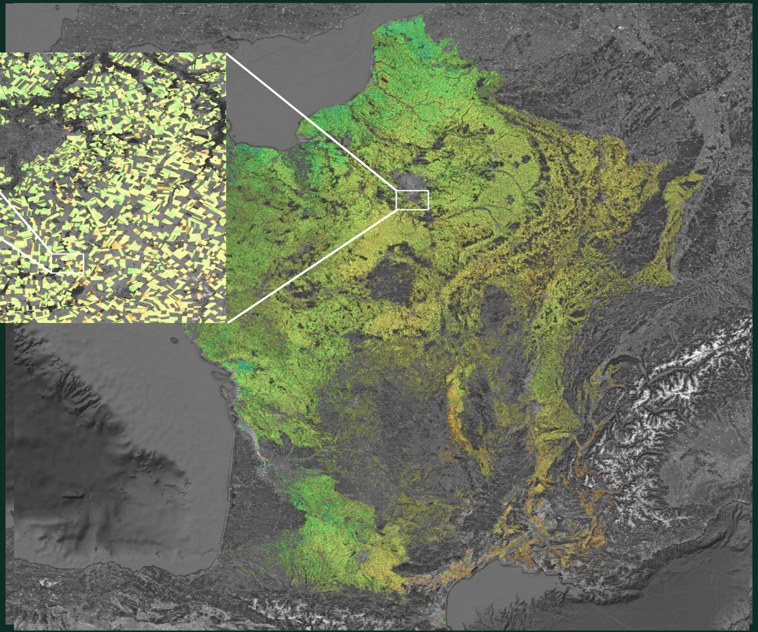
Coherent-set of agri-environmental variables ➔ scalable = applicable for NDC, CAP, VCM, insetting

Realisation: A. Al Bitar, V. Antonenko, L. Arnaud

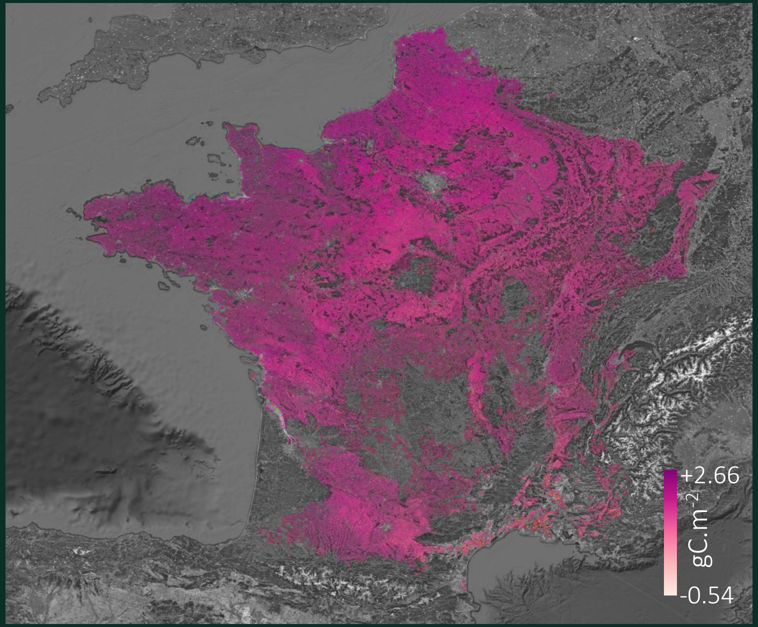


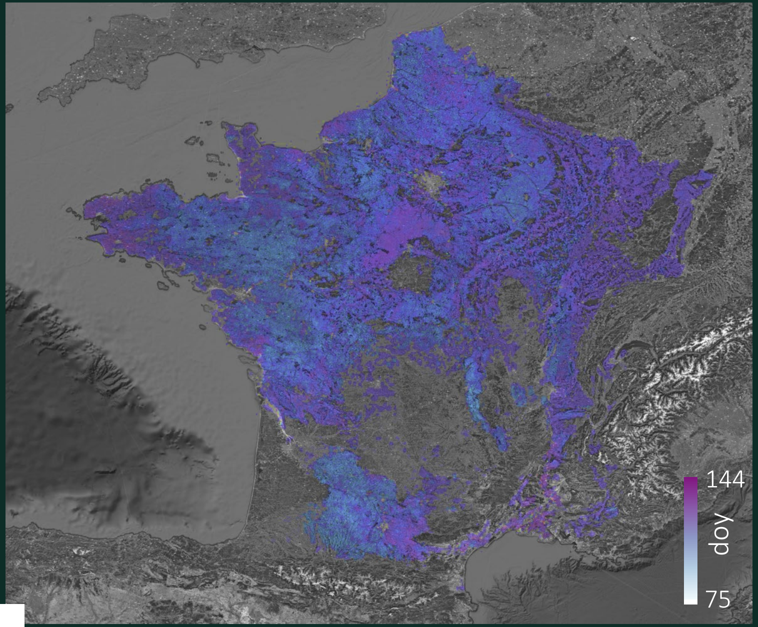


Dry Above ground biomass

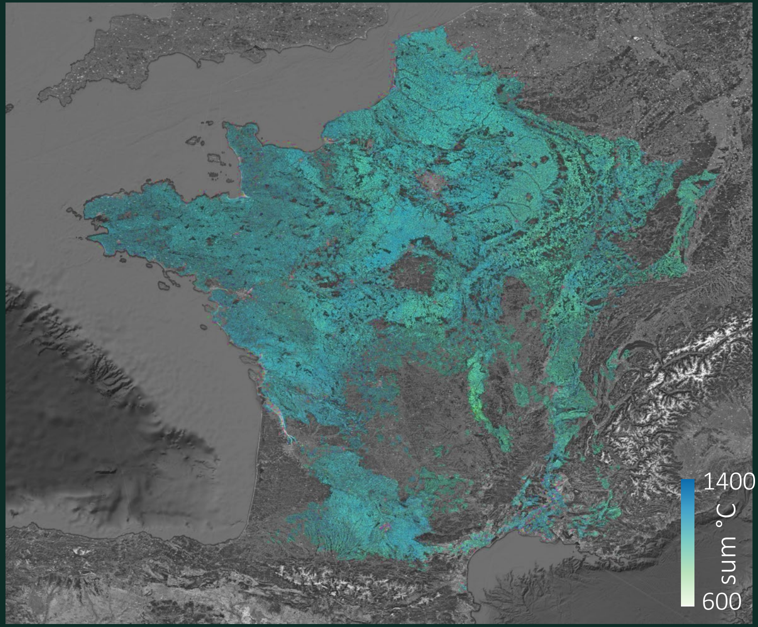


Net annual CO_2 flux

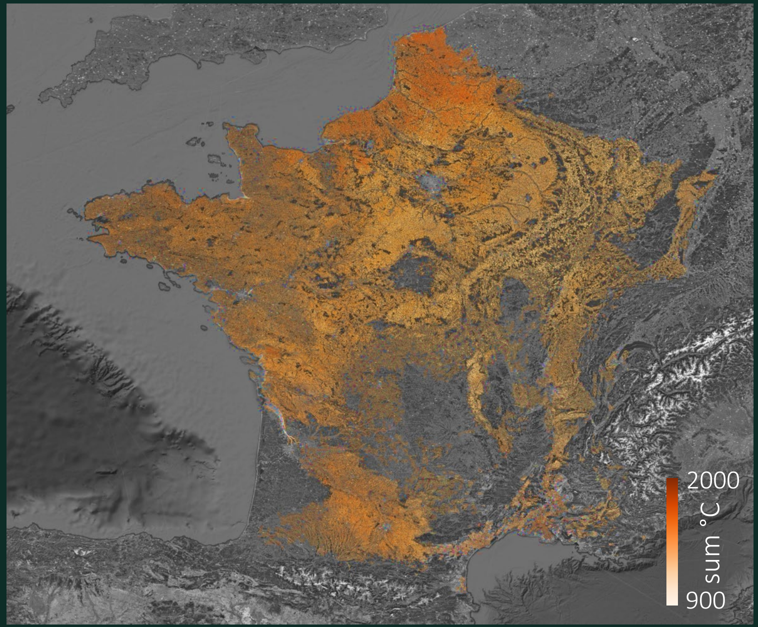




Day of emergence



Maturation phase



Senescent phase

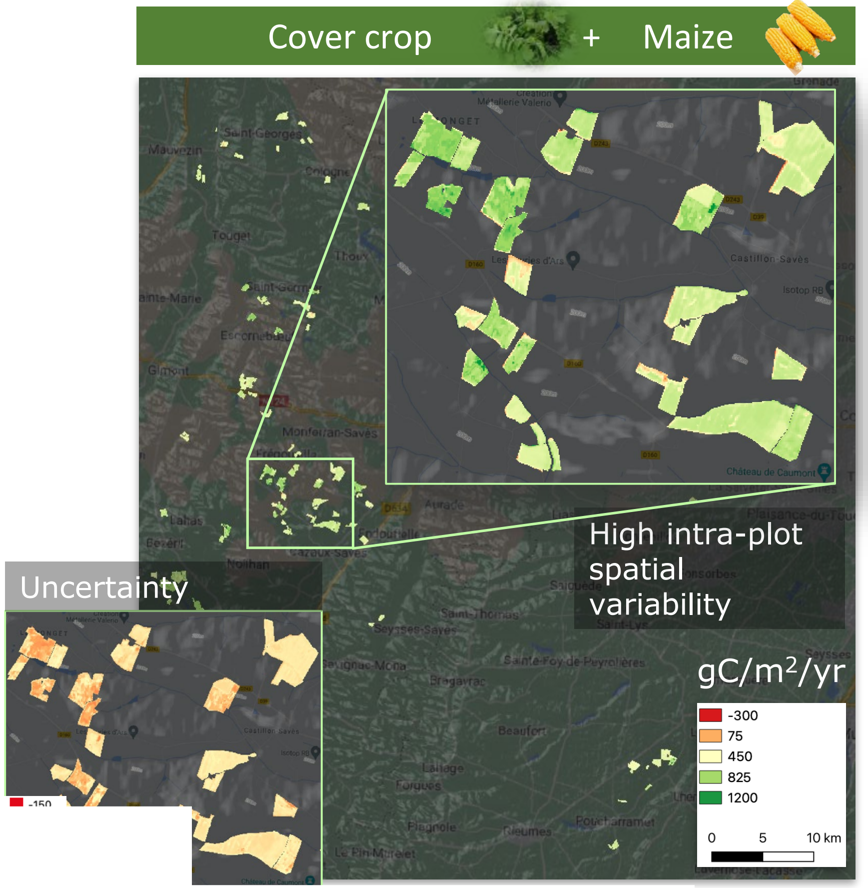
Effect of cover crops on the net annual CO_2 fluxes

Naturellement popcorn project ➔ farmers can receive a premium from the natais company depending on the amount of C they store in the soil thanks to cover crops biomass inputs (**insetting**)

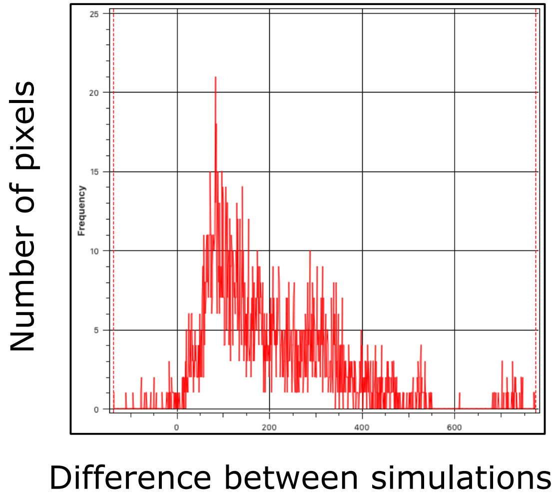
Over the double simulation exercice

Realisation A. Al Bitar

Reality

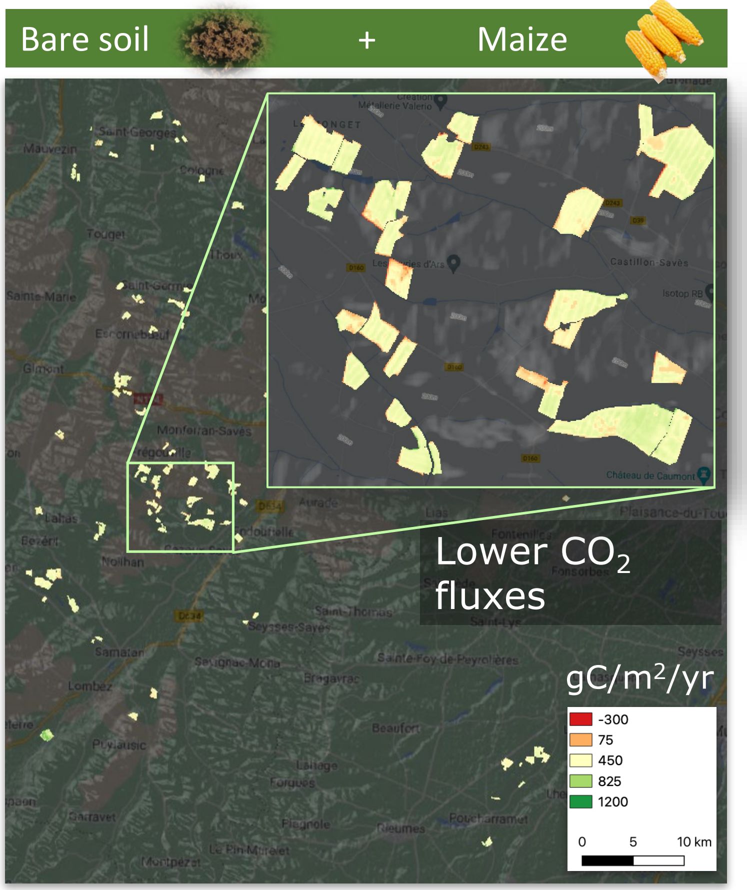


Distribution of the differences between the 2 simulations



On average 200gC of Dry Mass/ha/yr or approx 0,3 t C/ha stored/yr thanks to the cover crops

Neglecting the cover crop

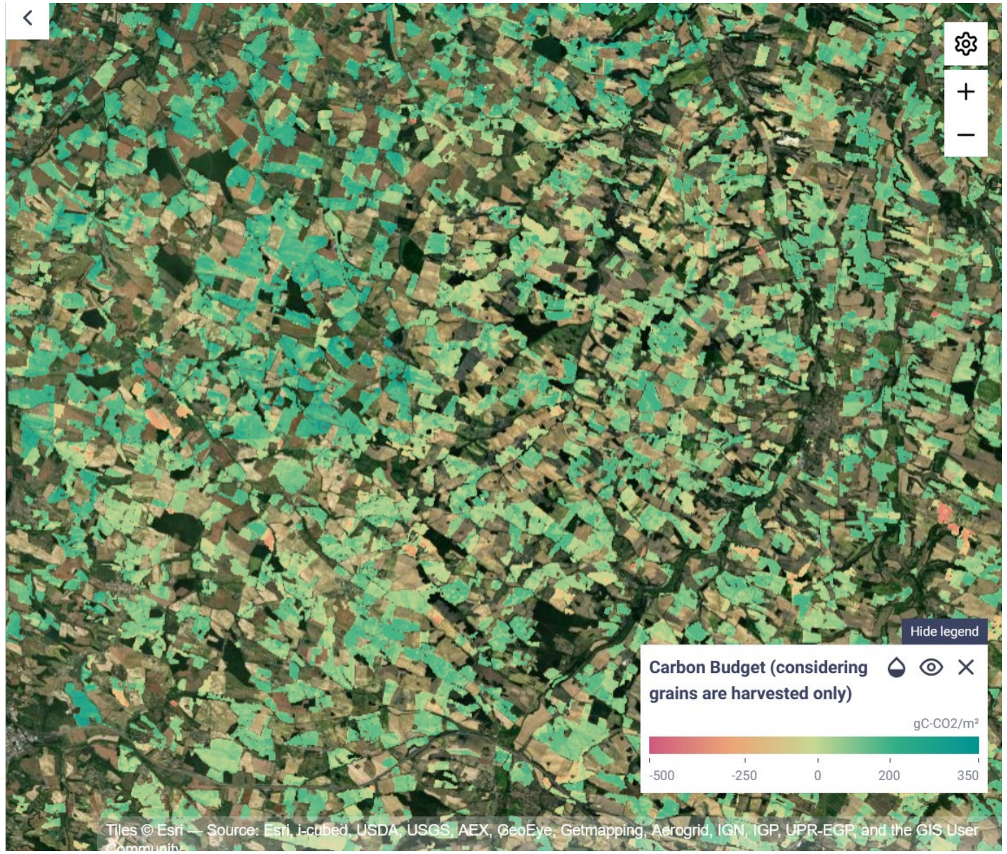


Effect of straw management on the annual SOC stock changes for straw cereals

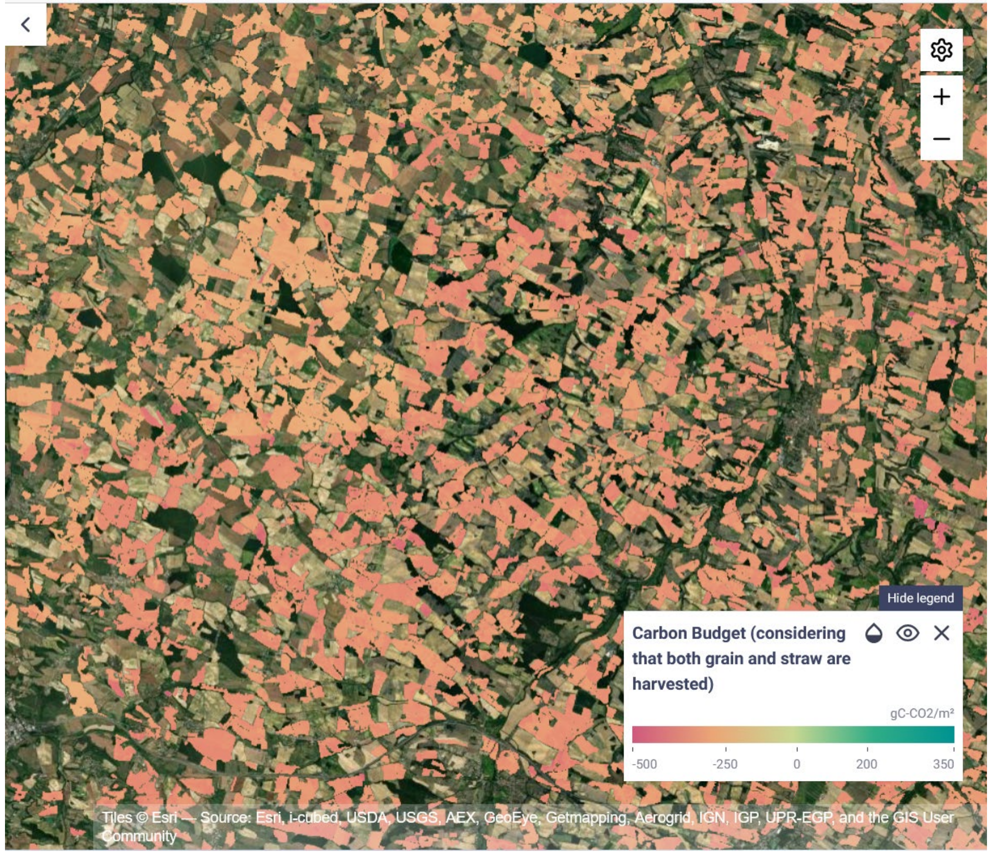
Simulation exercices near Toulouse (France) in 2019

More results at https://www.impact4soil.com/

Scenario 1: only grains are harvested and no organic amendment applied



Scenario 2: grains + straw are harvested and no organic amendment applied

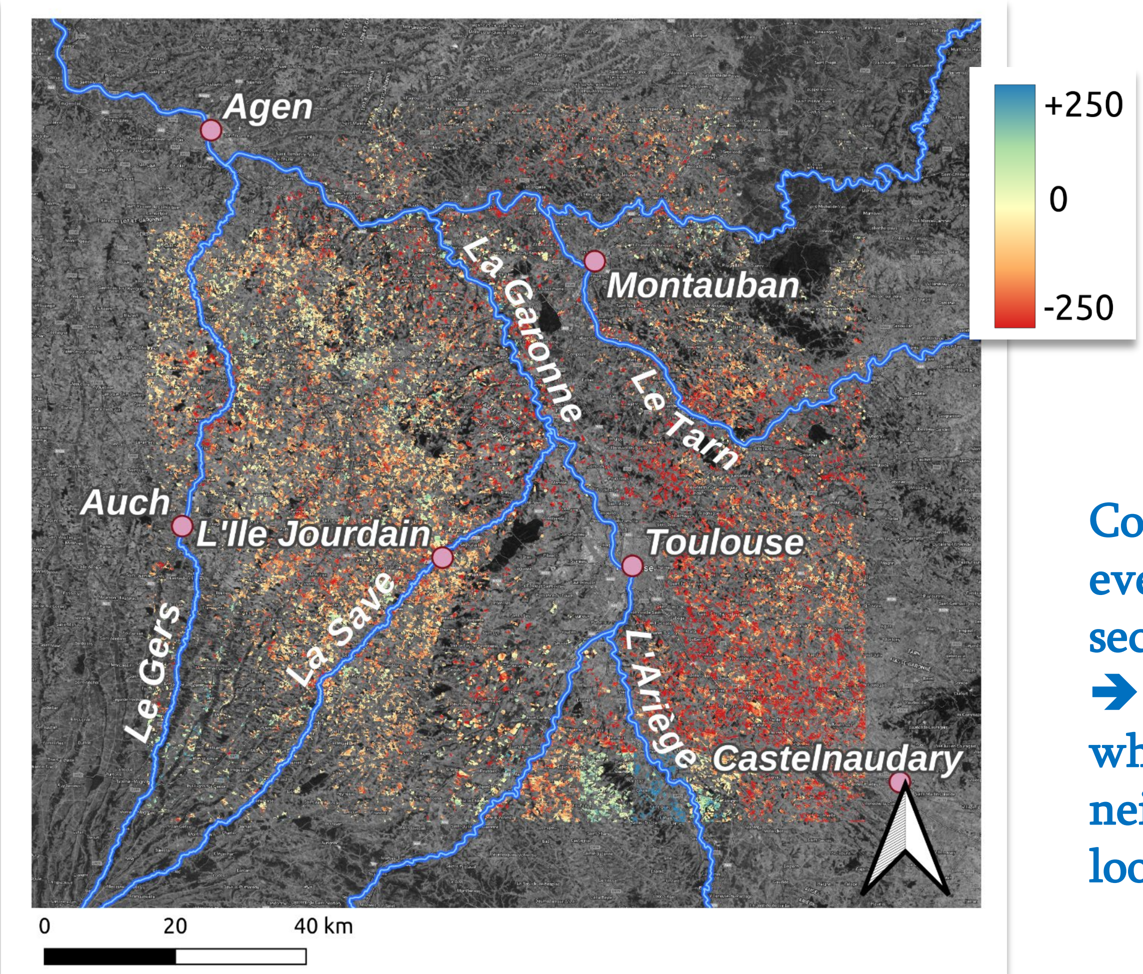


Diagnostic approach with realistic/objective assessment of biomass input to the soil but possible to test scenarii

Realisation A. Al Bitar

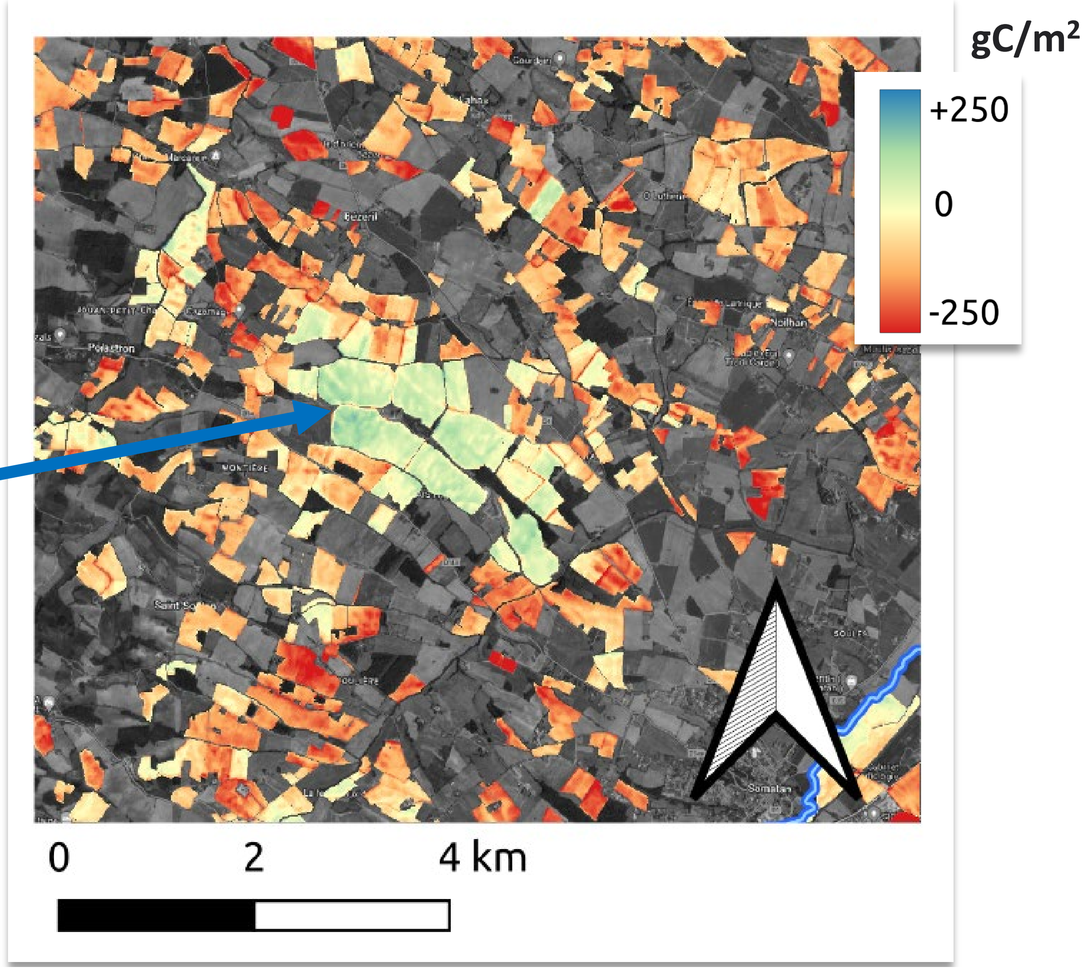
Soil Organic C Stock Changes over 5 years with ACEO V2.0 integrating AMG for the VCM

Simulating crop rotations with straw cereal, maize, sunflower & cover crops considering no organic amendment and straw retention



Villeneuve farm (wheat/maize rotation)

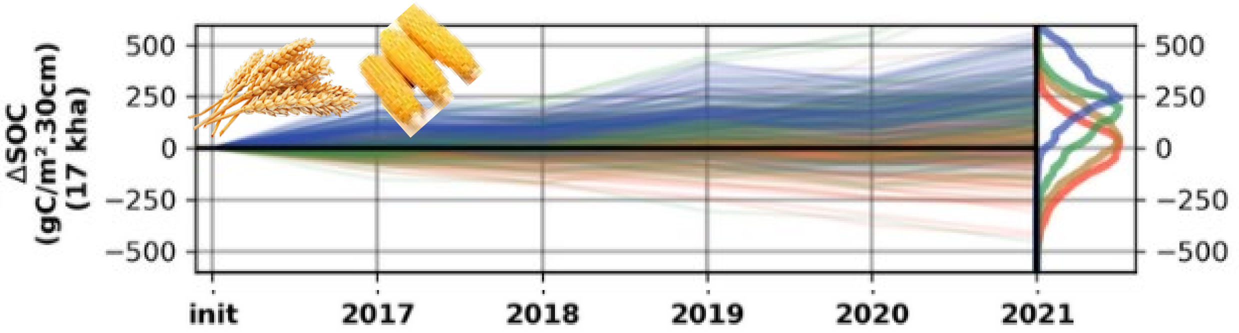
Cover crops every second year ➔ C storage while neighbors loose C



T. Wijmer PhD (2024) using LUCAS maps for soil properties and initialisation frac SOCa=0.4 (Delahaie et al., 2023)

Analyses of ΔSOC per crop rotations (gC/m2)

T. Wijmer PhD (2024)



0 cover crop

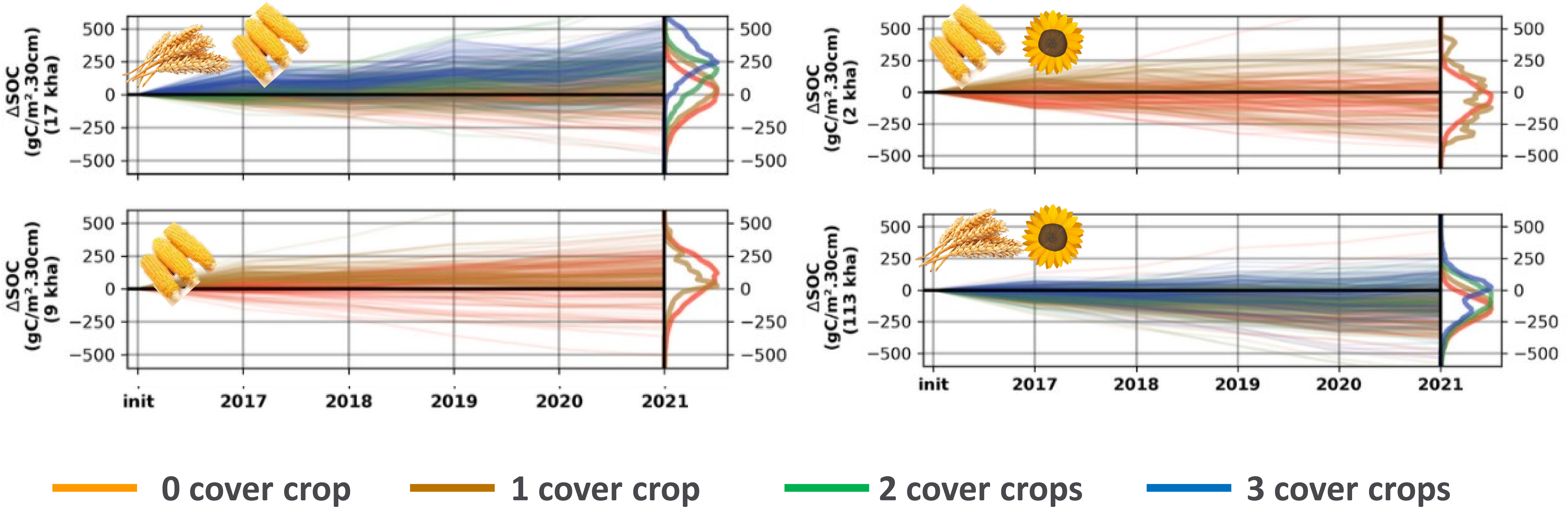
1 cover crop

2 cover crops

3 cover crops

Analyses of ΔSOC per crop rotations (gC/m2)

T. Wijmer PhD (2024)

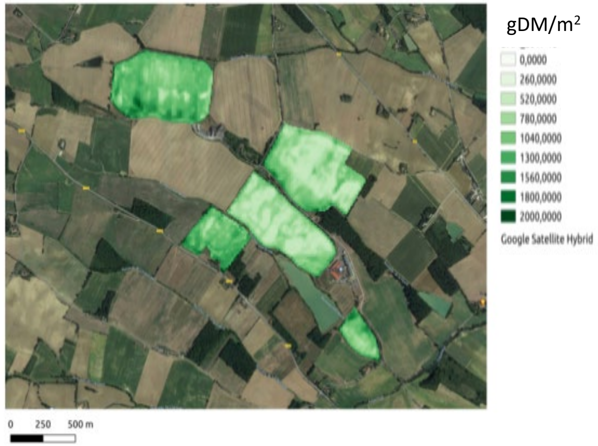


ACEO offers the possibility to produce plot specific baselines (e.g. for the insetting) and standardised (i.e. regional) baselines for the calculation of ΔSOC stocks in the context of VCM (compliant with CRCF methodology)

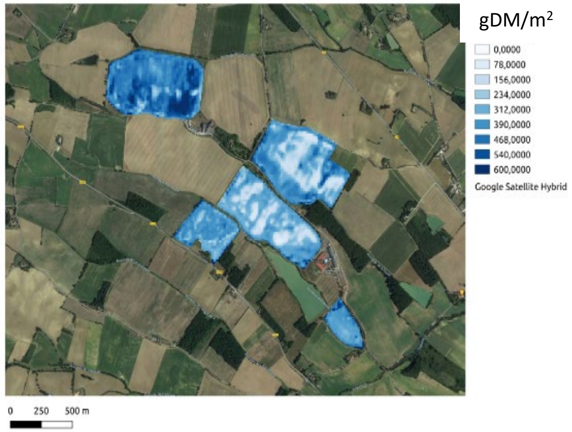
High resolution C budget maps with ACEO and verification strategy

Realisation
T. Wijmer

Crop biomass + Uncertainties



Cover crop biomass + Uncertainties



+ farmers data and the AMG soil model

10m resolution maps make it possible:

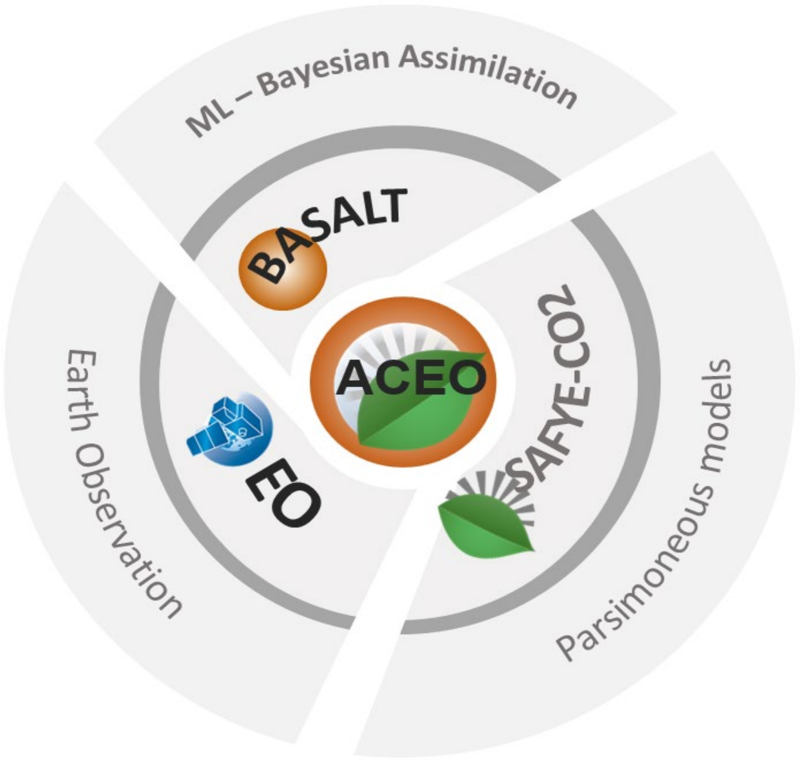
- to define an optimal cost/accuracy soil sampling scheme for verification of delta SOC stocks at plot/farm level
- to detect faster SOC stock changes by sampling areas with contrasted dynamics

First C budget map at 10m resolution in 2019, for rotation cover crop/corn/wheat (Villeneuve farm, Bézéril, France)

C storage by the soil

C losses by the soil

Hybrid ecosystem modelling approach dedicated to upscalling



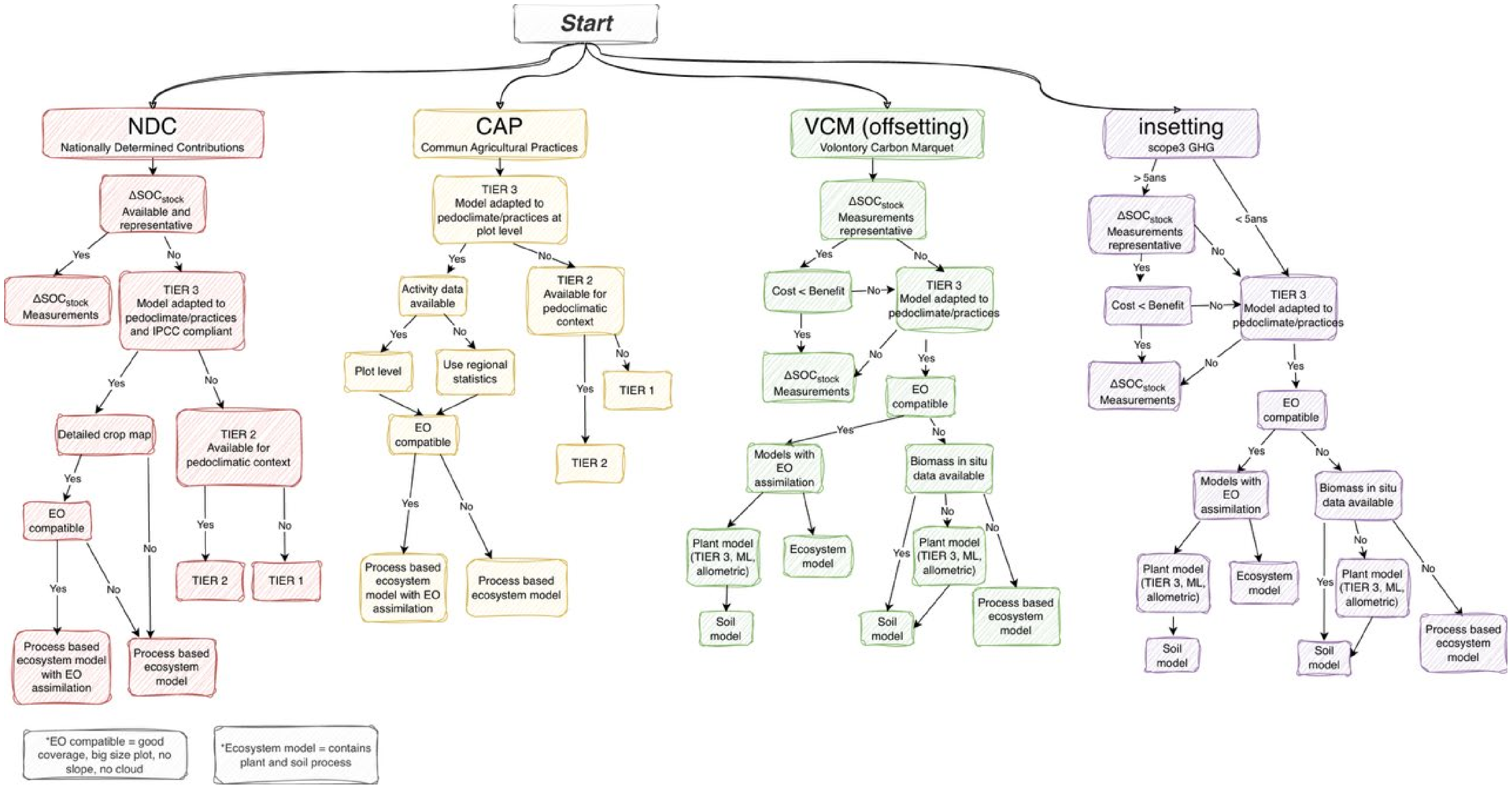
https://www.cesbio.cnrs.fr/agricarboneo/

Access to reliable management data on straw management and organic amendments is currently the strongest limitation with this approach (except in Spain, Netherlands?) → use of API to access FMIS is not enough, management data must be verified first (agricultural advisor)

- **Not user friendly & good skills in programming**
- **Main crops & some cover crops**
- **Pixel level → best for validation/verification**
- **Cost depends on activity data collection method and soil sampling scheme for initialisation/ verification**
- **Scalability (except long cloudy periods → radar satellite data)**
- **Uncertainty assessment**
- **Accuracy depends on access or not to local soil data, on accuracy of activity data (but less problematic than with classical crop models).**
- **Same tool whatever the context of application + baselines production (generic or specific) → compliant with the CRCF**

Decision tree to choose the Monitoring approach best suited

Even if ACEO is a very promising approach it won't be applicable in all contexts (e.g. very small plots, agroforesteries, crop species not simulated…) ➔ need a decision tree to choose the best approach depending on the local context



Final version made available by ORCASA at the end of the year (Ihasusta et al. in prep)

Conclusions

- As pointed out by CIRCASA/ORCaSa ➔ need to develop new monitoring methods and a consistent framework for MRV of SOC stock changes for different context of application (NDC, VCM insetting, CAP),

- Based on this **observation and after analysing the pro & cons of current modelling approaches for monitoring SOC stock changes ➔** development of AgriCarbon-EO, an innovative hybrid monitoring approach assimilating remote sensing data in a crop model dedicated to upscaling:

  - enabling dynamic and more objective/realistic monitoring of the impact of biomass restitution to the soil on the SOC stock changes

  - automated, large scale, high resolution, allowing uncertainty analysis at low cost adapted to different contexts of MRV and compliant with common standards like VERRA, Label Bas Carbone and the CRCF ➔ e.g. able to produce both specific and standardised baselines

  - Yet improvements are needed: to ensure the operationality of ACEO even in cloudy conditions (radar satellite data), simulate more crop/cover crop species, coupling other soil models to SAFYE-CO2 (e.g. for ensemble approaches),

- **Also it is not a one fit for all solution and some challenges remain whatever the modelling approach:**

  - Reduce uncertainty on soil properties, initial SOC stocks and fraction of stable SOC (e.g. Rock-Eval®)

  - Access to reliable activity data, especially for large scale applications (e.g. CAP)

Thanks for your attention!!

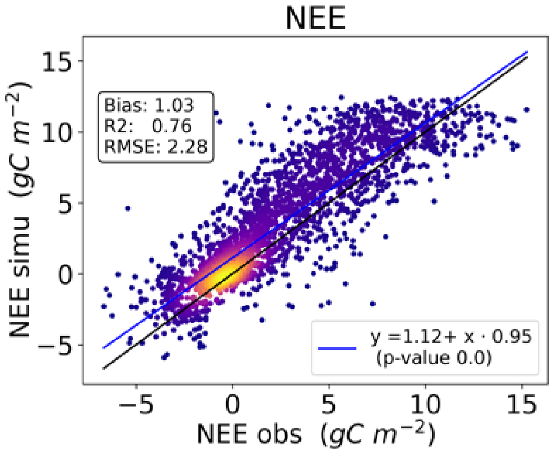
Naturellement popcorn

More about our work: https://www.cesbio.cnrs.fr/agricarboneo/

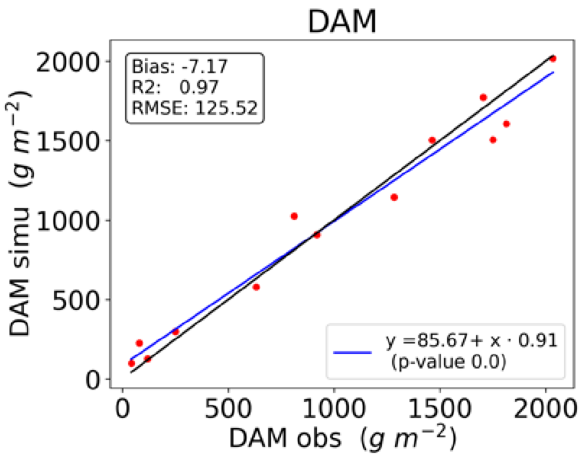
Contact : eric.ceschia@inrae.fr and ahmad.albitar@gmx.com

Validation exercises for the C budget components

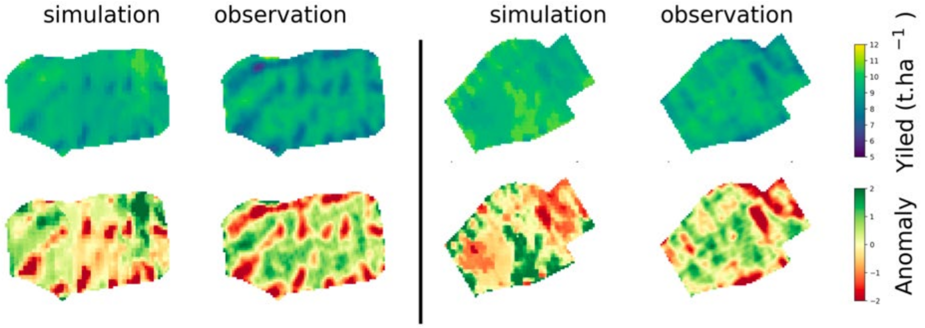
ICOS Integrated Carbon Observation System



Net CO_2 flux for wheat in Europe at ICOS sites

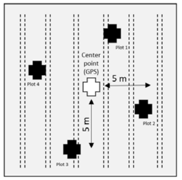


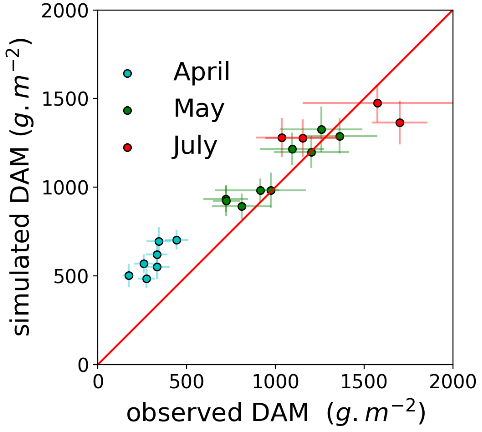
Biomass for wheat in Europe at ICOS sites



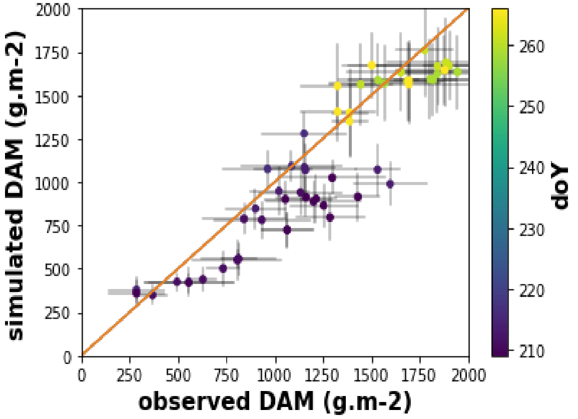
Winter wheat yield maps

Biomass with ESU protocol

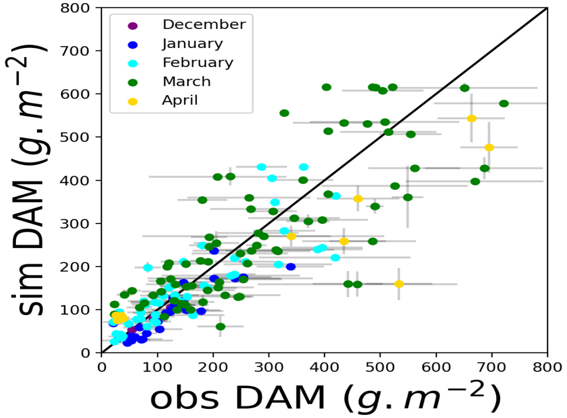




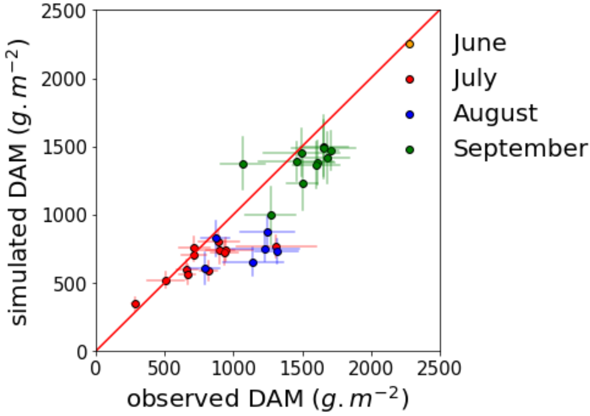
Biomass for Wheat in France



Biomass for Maize in France



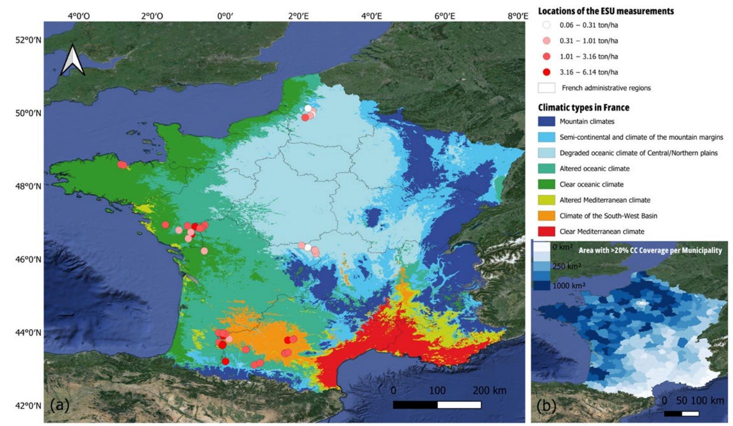
Cover crops (Fava bean) in France



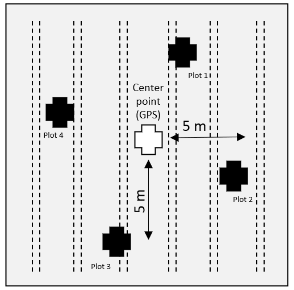
Tomato in Italy

More crops to come but no validation against ΔSOC stock changes yet because data with measures and re-measures since Sentinel 2 data were launched are not missing

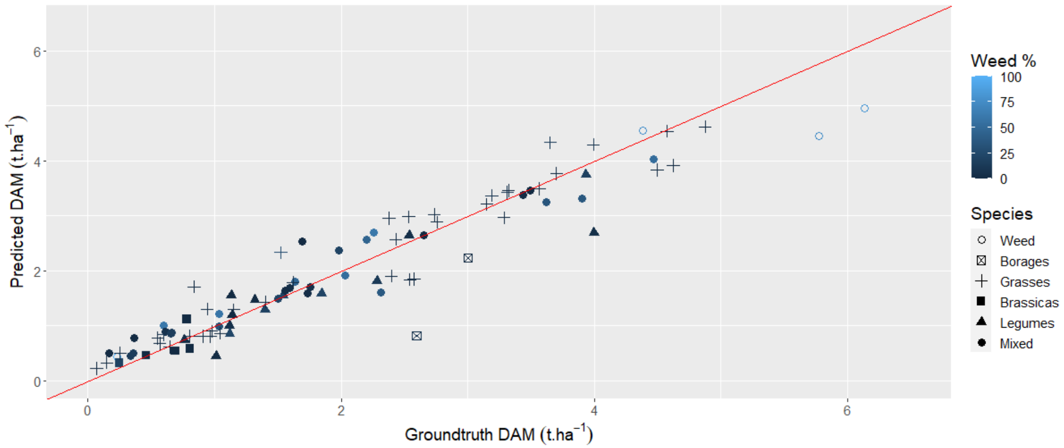
Remote sensing + ML to estimate cover crop biomass spatial variability and C inputs

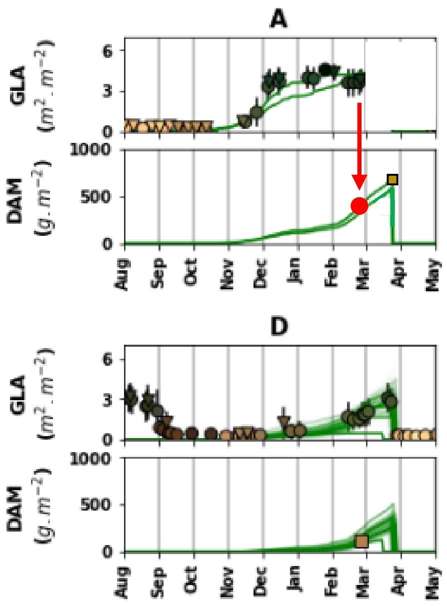


do Nascimento Bendini et al. (2014)



Example of ESU protocol
See T2.3 !!!





Good performance with ML but:

- little year to year transposability ➔ requires multi-year training dataset
- **Good estimates at the date of acquisition** but what happens if 2-3 weeks of clouds ? (cover crop biomass can double every week in spring !!!) ➔ need to combine this approach with crop modelling to interpolate/extrapolate biomass estimates

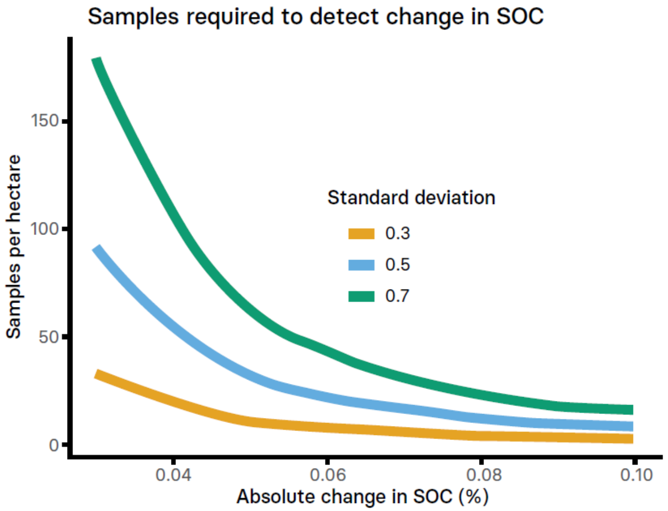
Green curves are AgriCarbon-EO simulations (see next slides), dots are observations

What is the C budget of an agricultural plot? And how to quantify it?

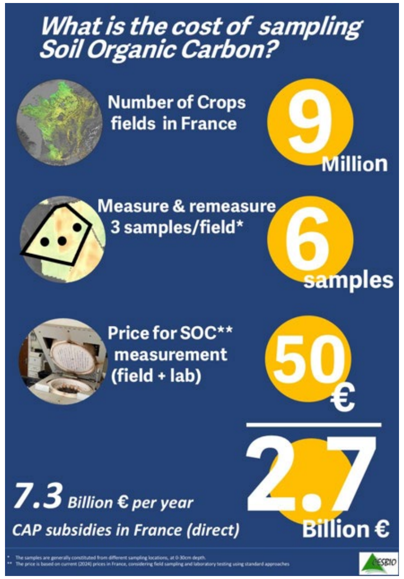
- The C budget represents a carbon gain or loss of a soil, mainly in the form of organic matter, between two dates (crop year, rotation, etc.)

Measure - remeasure of soil organic C stocks

- Requires a large number of samples between 2 dates ➔ very expensive, high uncertainty, risk of unrepresentative sampling (can be reduced by mapping soil properties ➔ stratified sampling)



D'après EDF.ORG/SOILCARBON



A. Al Bitar

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Measure - remeasure of soil organic C stocks

- Requires a large number of samples between 2 dates ➔ very expensive, high uncertainty, risk of unrepresentative sampling (can be reduced by mapping soil properties ➔ stratified sampling)

C budget approach = accounting for inputs & outputs of C

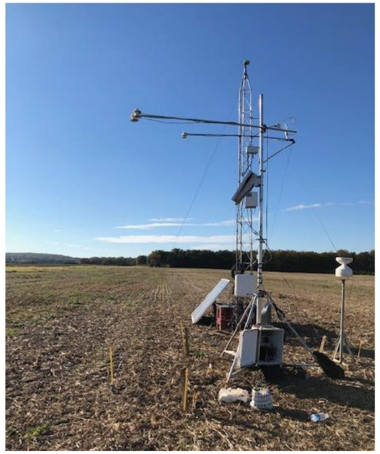
- More dynamic approach but quantification of all fluxes (vertical/lateral) of C between the parcel and its environment (by measurements or via modelling) ➔ see Smith et al 2010

A carbon budget approach to estimate SOC stocks changes

Béziat et al. (2009) in AFM
Ceschia et al. (2010) in AGEE
Smith et al. (2010) in AGEE

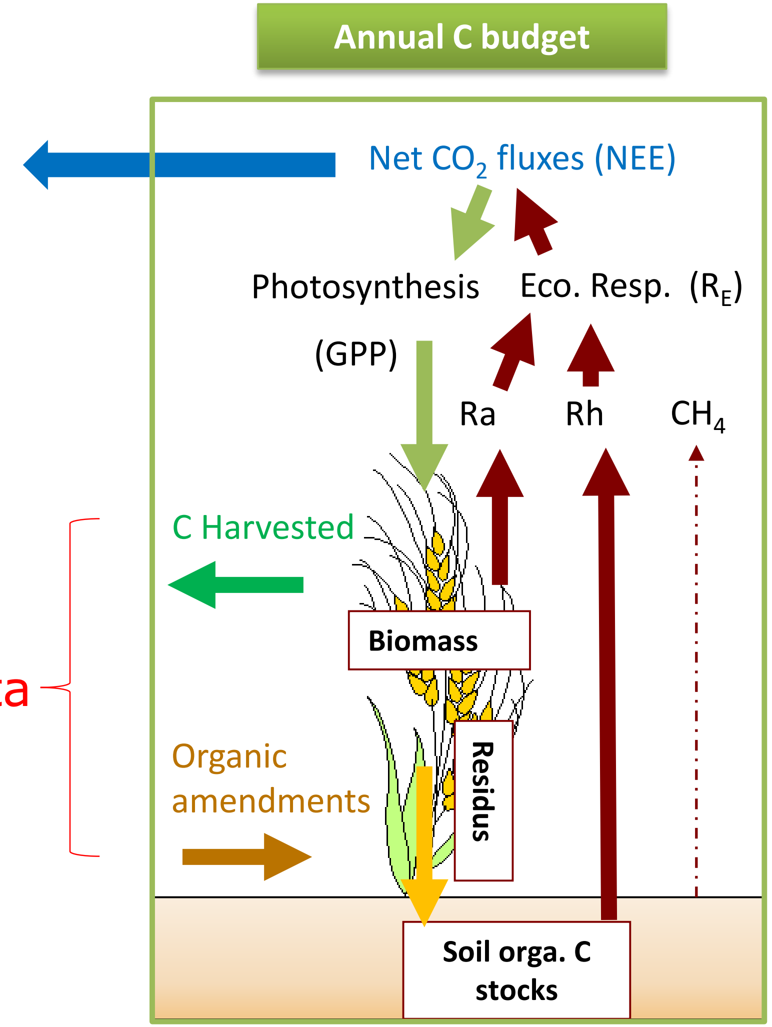
Yearly ΔSOC stock = Net CO_2 flux + C_{import} - C_{export}

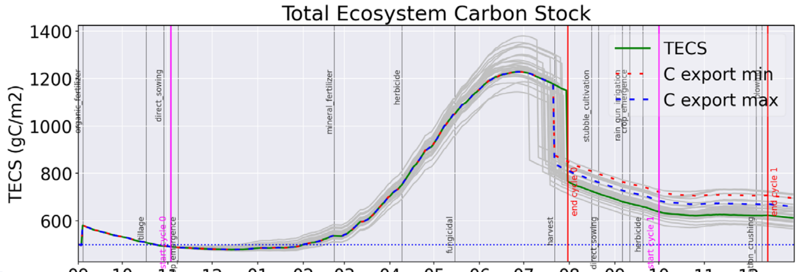
Models or



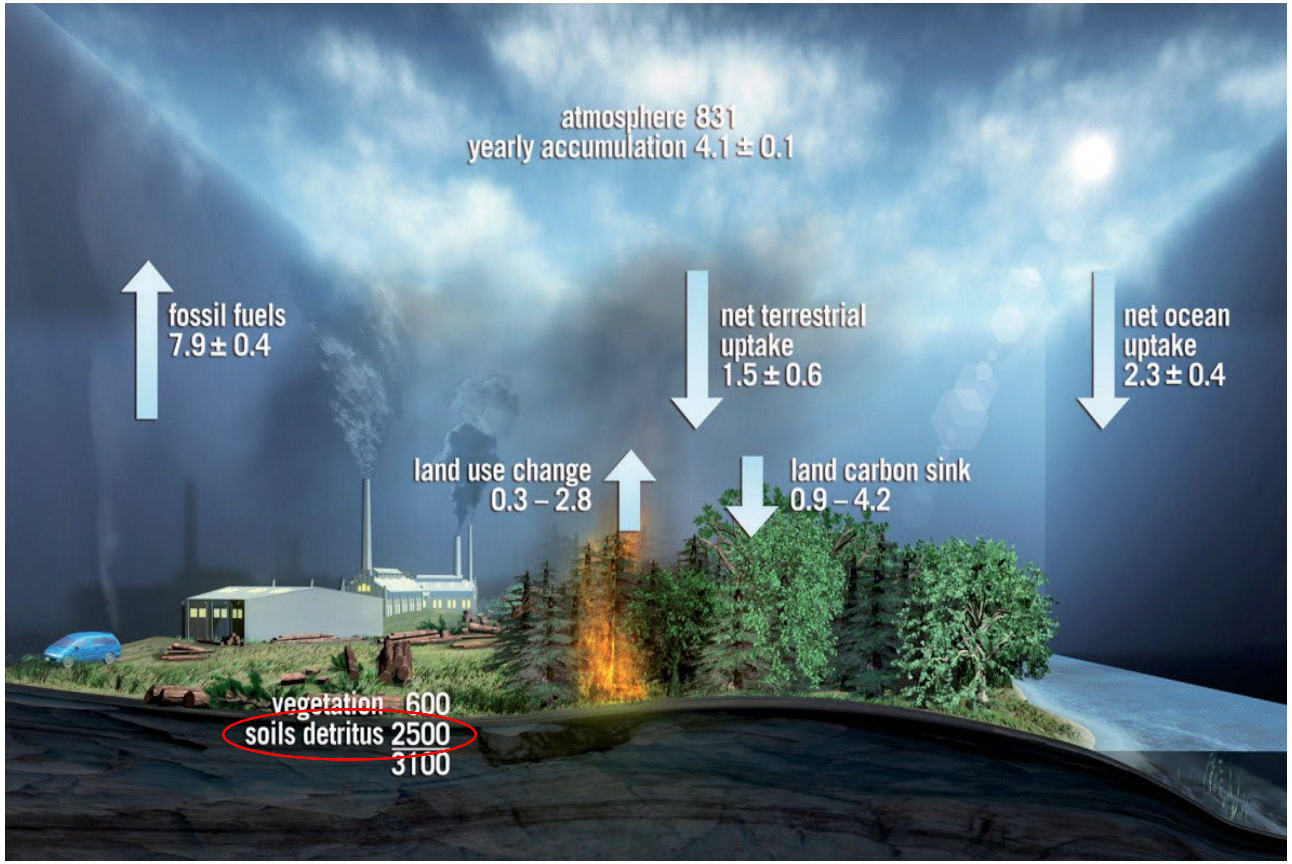
Flux tower

Farmer's data





Soils, a large carbon reservoir but with great disparities

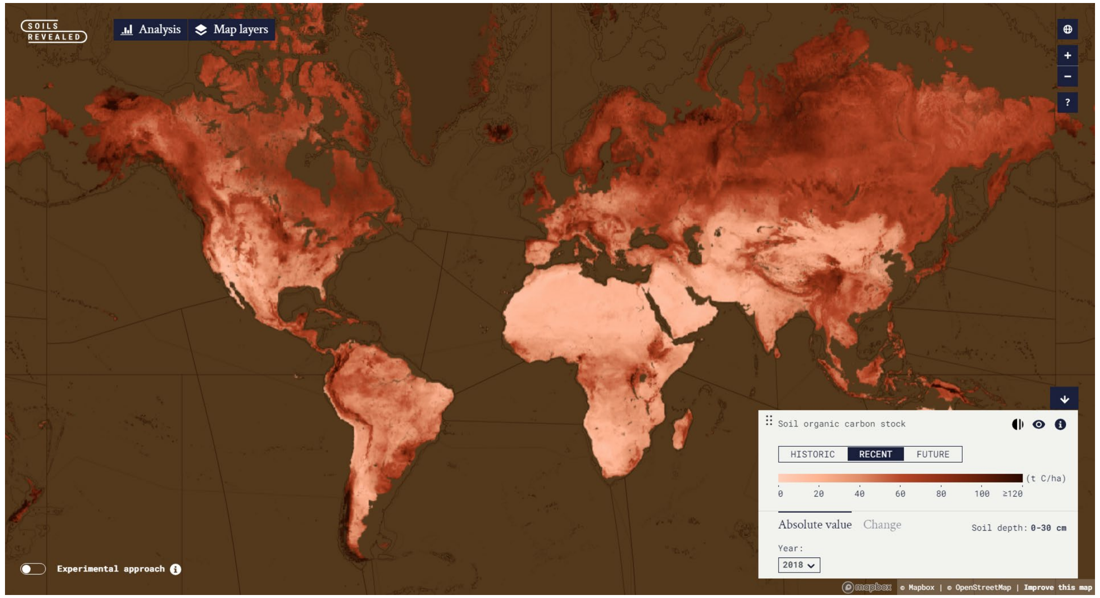


in Giga tonne

- **Carbon is present in soils in large quantities as more or less decomposed organic matter (e.g. leaf and root debris, humus, organo-mineral associations)**

- **But strong spatial variability of stocks partly related to human activities**

Spatial variability of soil organic carbon (SOC) stocks on the 0-30 cm layer in the world



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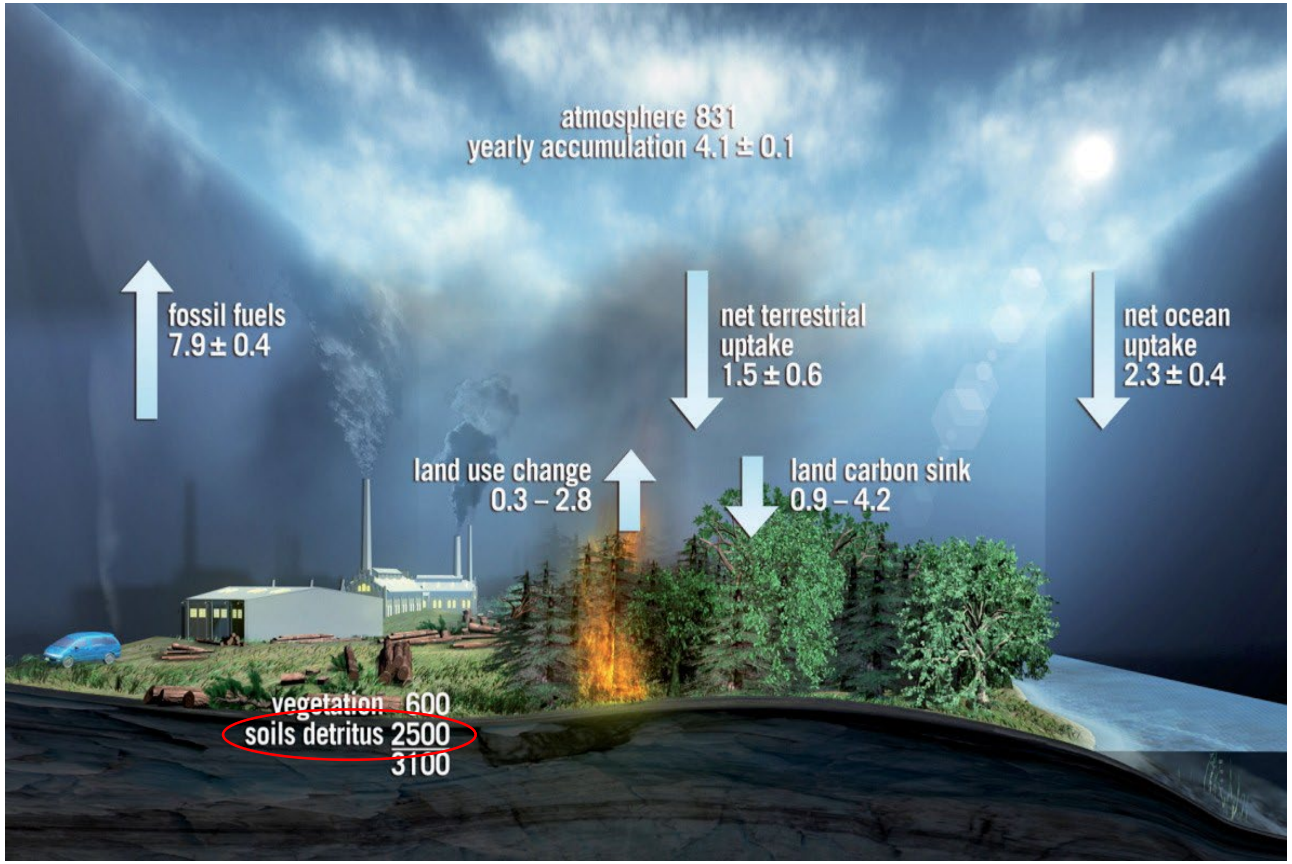

in Giga tonne

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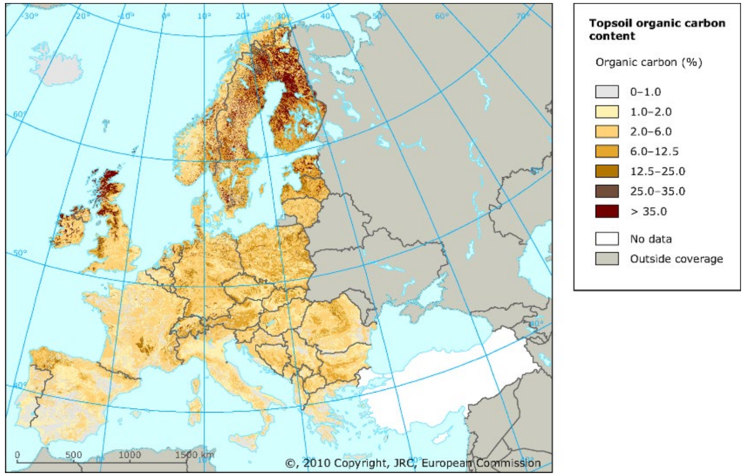
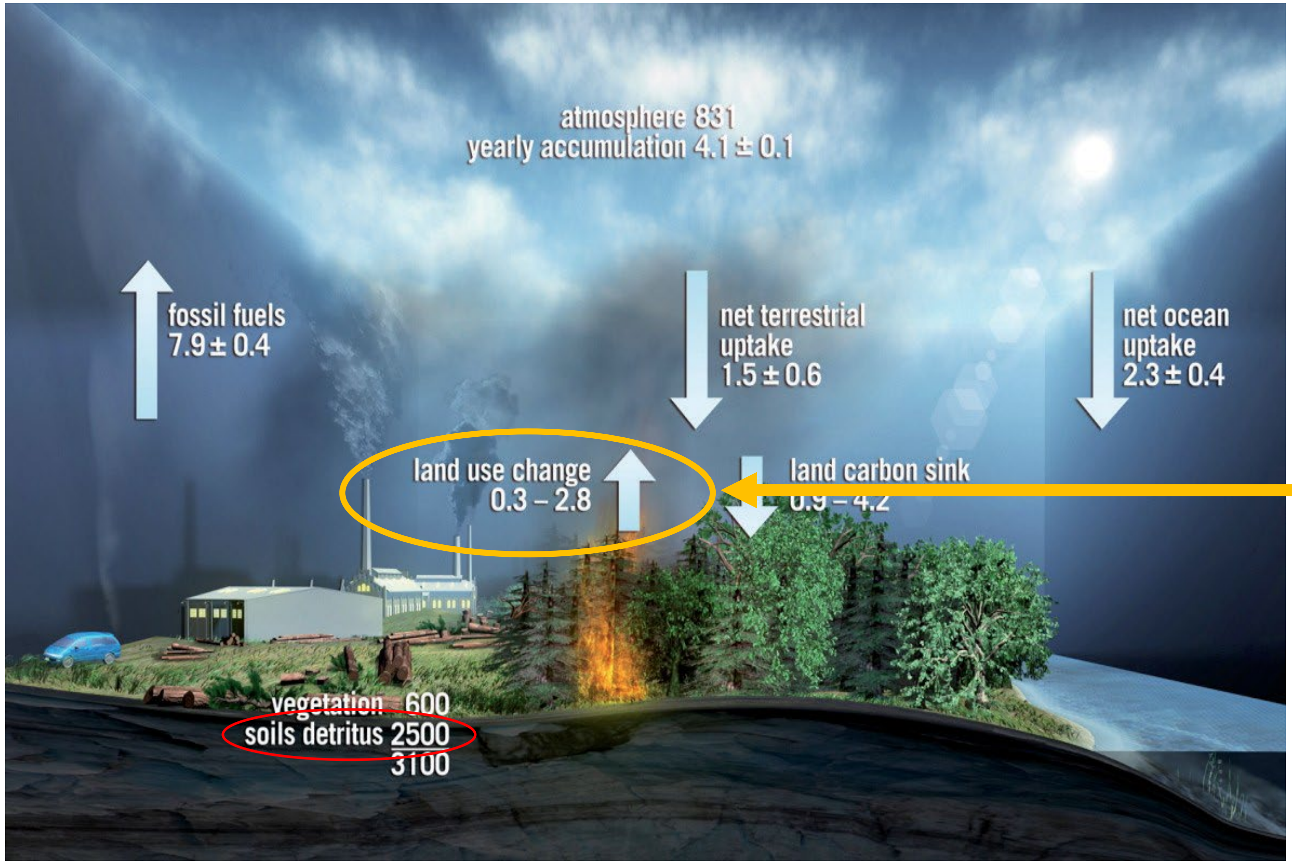
Spatial variability of soil organic carbon (SOC) stocks on the 0-30 cm layer in Europe



Soil C content
Peatland >>> grassland > forest >> cropland

Soils, a large carbon reservoir but with great disparities



in Giga tonne

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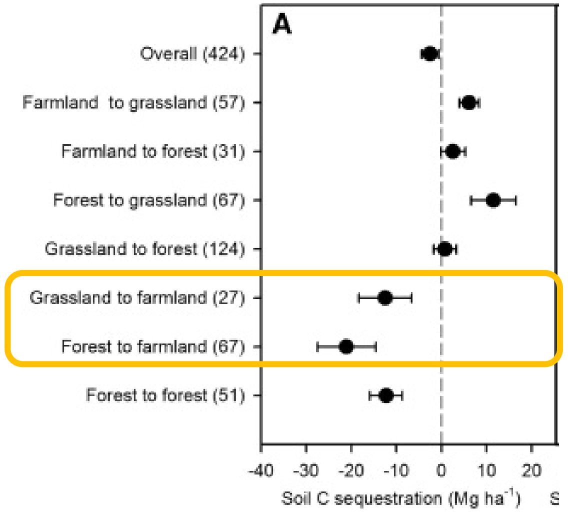
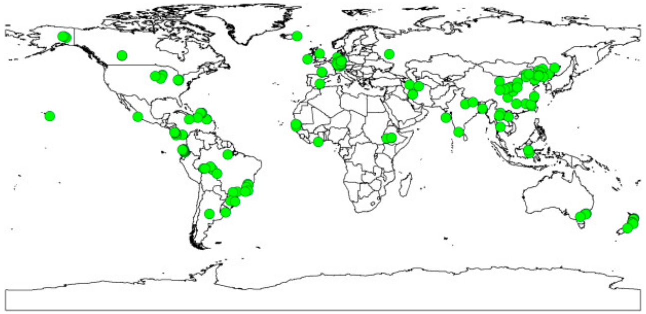
- **But strong spatial variability of stocks partly related to human activities**

Effect of land use changes on SOC stocks (Deng et al. 2016)





Inventory approach

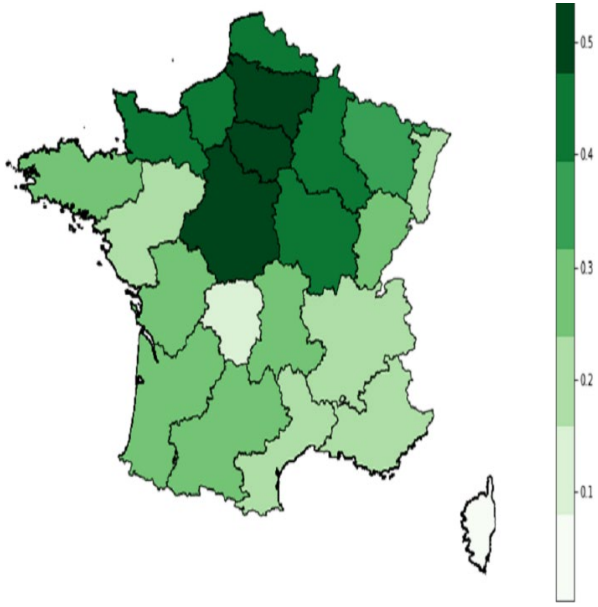
Increasing Soil Organic Carbon stocks, a climate and food security issue

Increasing SOC stocks in soils by 0.4% (or 4 per 1000) per year would offset global annual CO_2 emissions but it would also increase soil fertility and crop resilience to climatic extremes ➔ **but where and how ?**

National expertise : Stocker du carbone dans les sols français. Quel potentiel et à quel coût ? (Pellerin et al. 2019) ➔ national statistics (practices), STICS agronomic model + several scénarii (see Launay et al 2021b).

- Additional C storage potential of 5.78 Mt C/year in the 0-30 cm soil layer (approximately 8.6 Mt C/year if we consider no cover crops at all in the reference scenario)
- It represents an annual increase of:
  - +5,2 (to +8,3 %) of SOC stocks for the arable lands ➔ 62 % of this effect comes from the cover crops
  - +0,9 % for the grasslands

Additional C storage potential in tC/ha/yr



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Exemples of cover crops