Analysing carbon, GHGs and energy fluxes/budgets of agro-ecosystems for more efficient climate change mitigation strategies: approaches combining in situ data, modelling and remote sensing

Eric Ceschia

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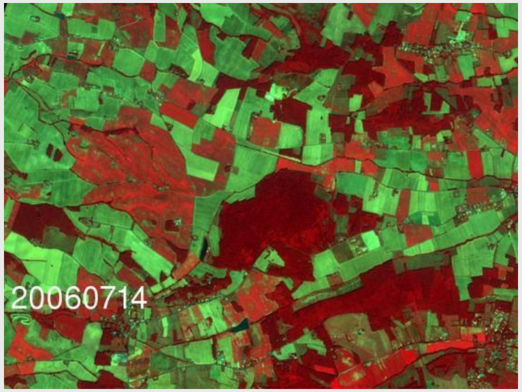

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Part 1

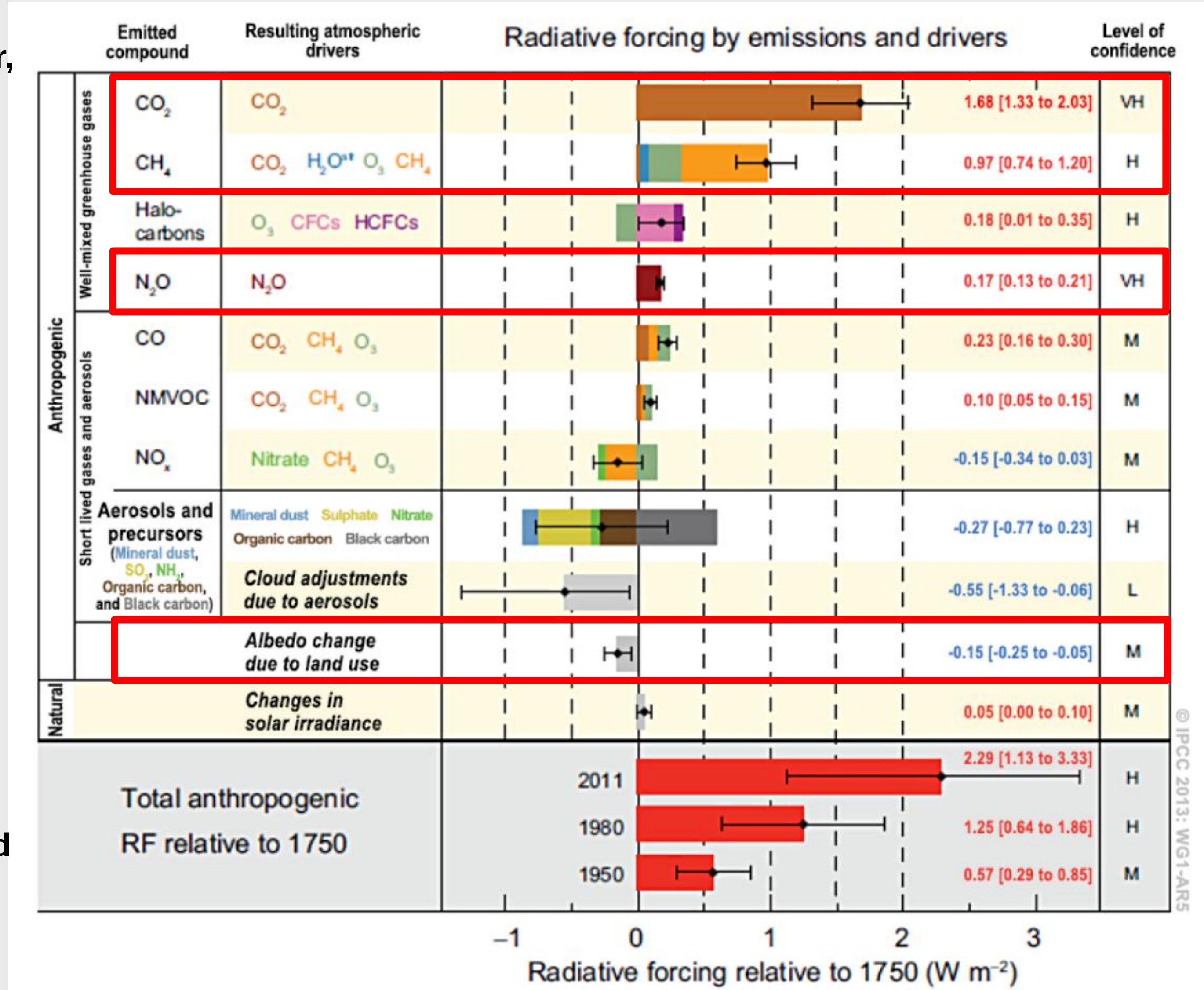
- General context
- Analysing the processes affecting climate for cropland
- Identifying climate mitigation levers
- Defining efficient strategies for climate mitigation by adapting cropland management

The causes of global warming

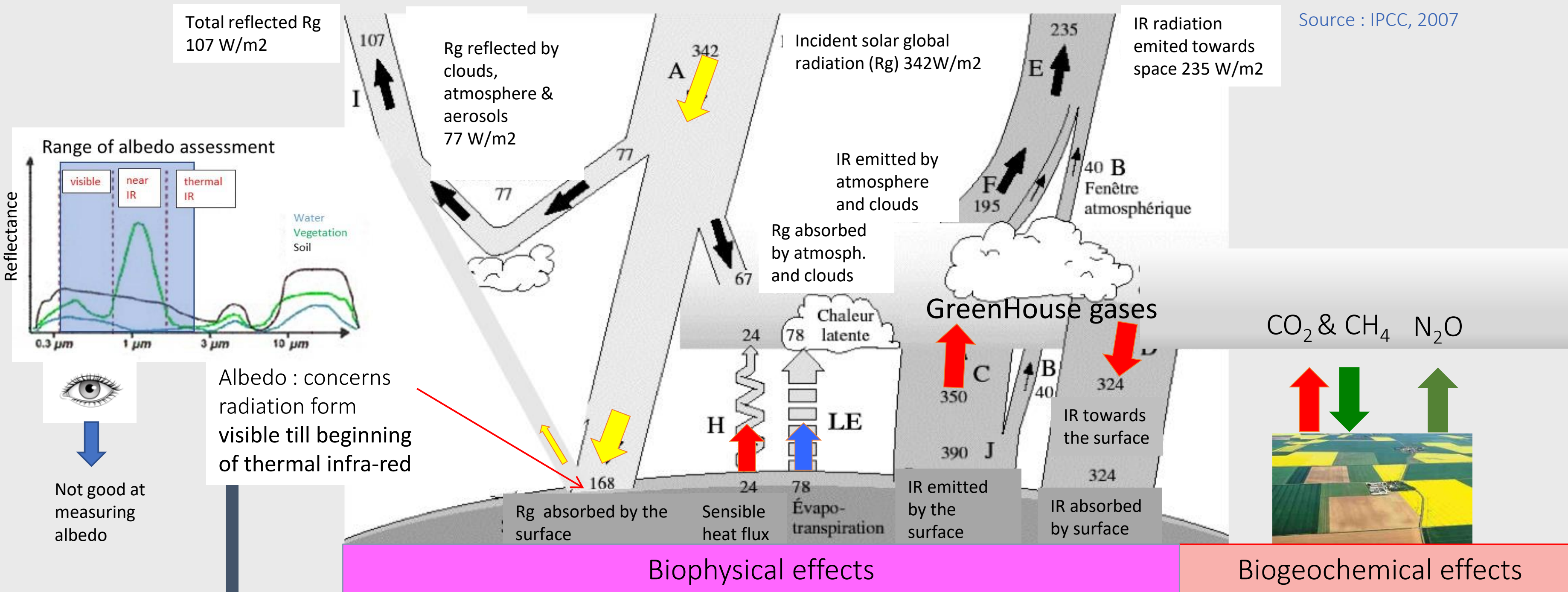
Albedo effects accounted for, but :

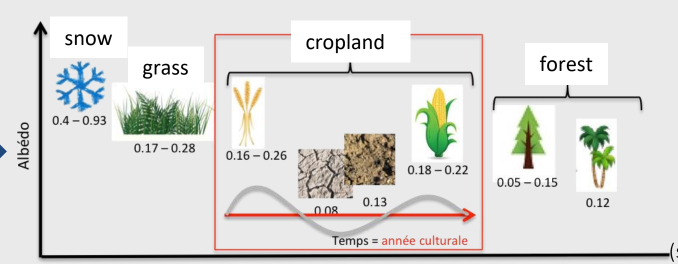
- IPCC models are way too simplistic & inacurate concerning continental surfaces because:
    - poor diversity in vegetation species ➔ only wheat&maize for crops in most/all models,
    - no accounting of management practices,
    - Low accuracy of input data (land use type desciption, spatial resolution of the input data…)

➔ Inacurate albedo effects & identification of associated levers for climate mitigation and very likely underestimated because…



The causes of global warming



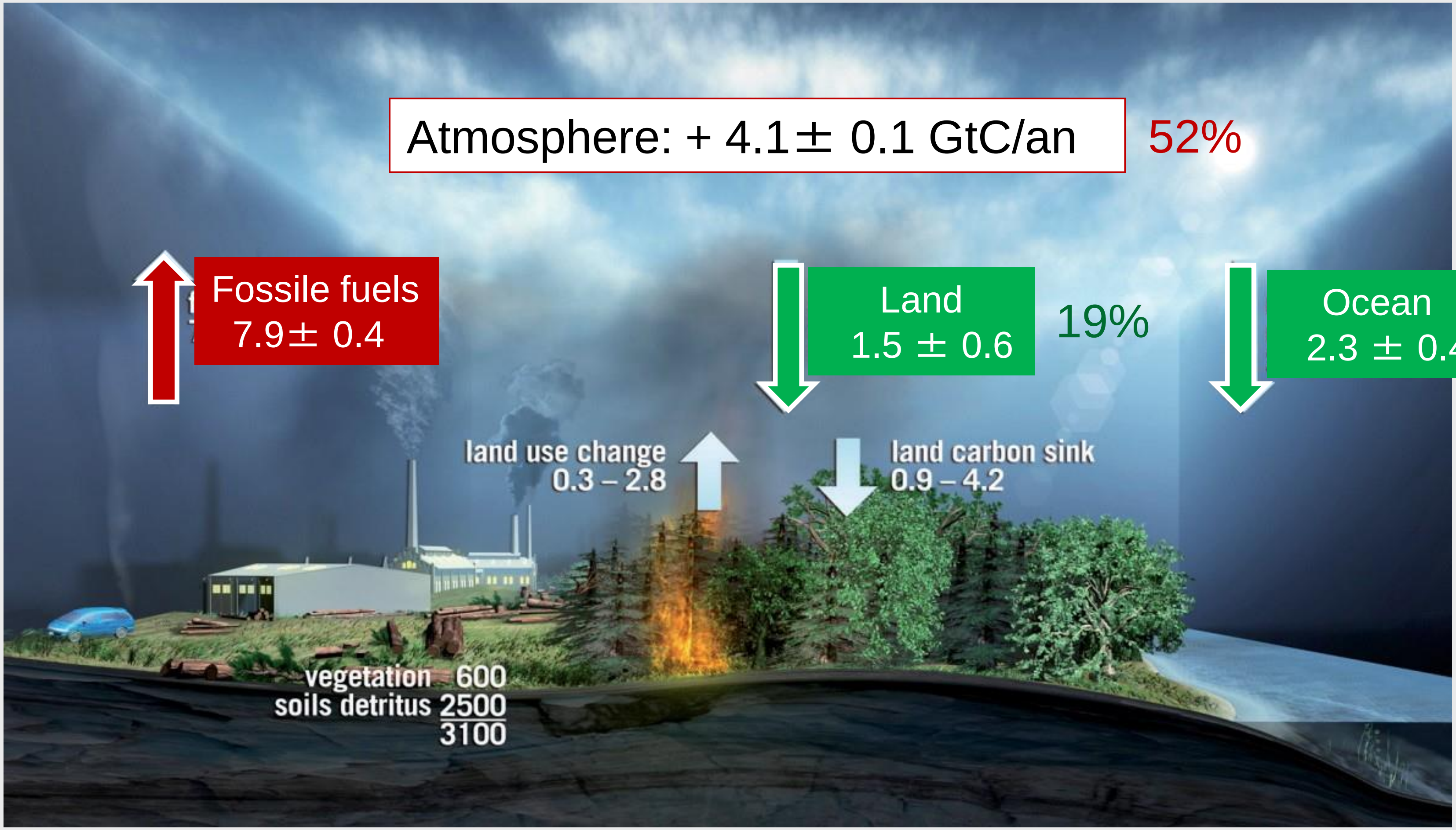


(source : *Carrer et al., 2013*)

Energy available at the surface: Rn = (1-α) x Rg = LE + H + G + photosynthesis

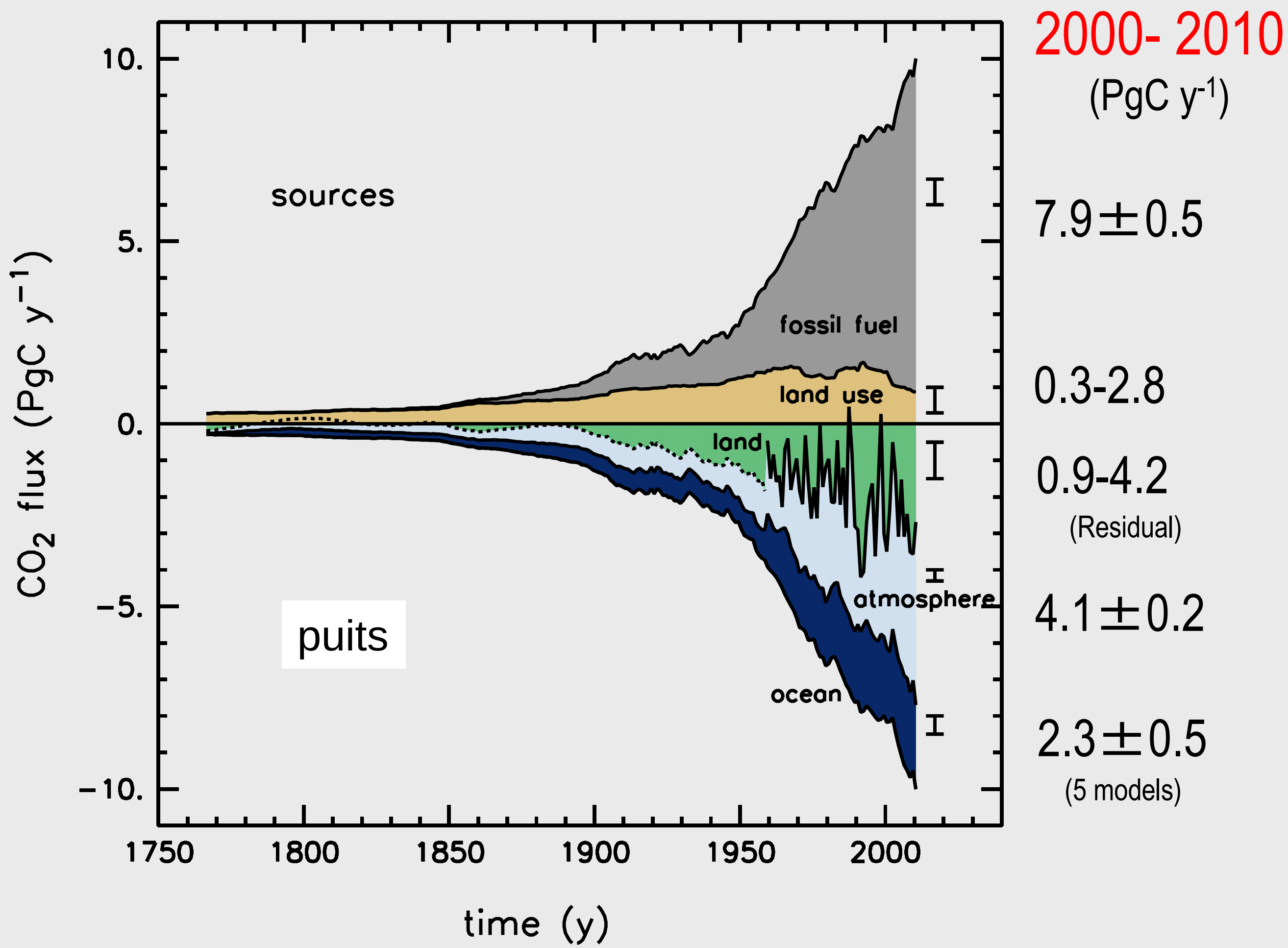
- Photosynthesis ➔ max 4%
- Latent heat flux (LE = evapotranspiration) ➔ 70% on global average
- Sensible heat flux (H) ➔ 20 – 30 % on global average
- Soil heat flux (G) ➔ less than 10%

A focus on the carbon cycle 2000-2009



1 Giga tonne = 10^9 tonne (1 billion of tonnes)

The global carbon budget



Global Carbon Project 2011; Updated from Le Quéré et al. 2009, Nature G; Canadell et al. 2007, PNAS, Friedlingstein et al., 2010

High uncertainty in the share of land surfaces in the global C budget

Effect of Land Use Change on Soil C Stocks

Guo & Gifford 2002, Global Change Biology 8, 345-360.

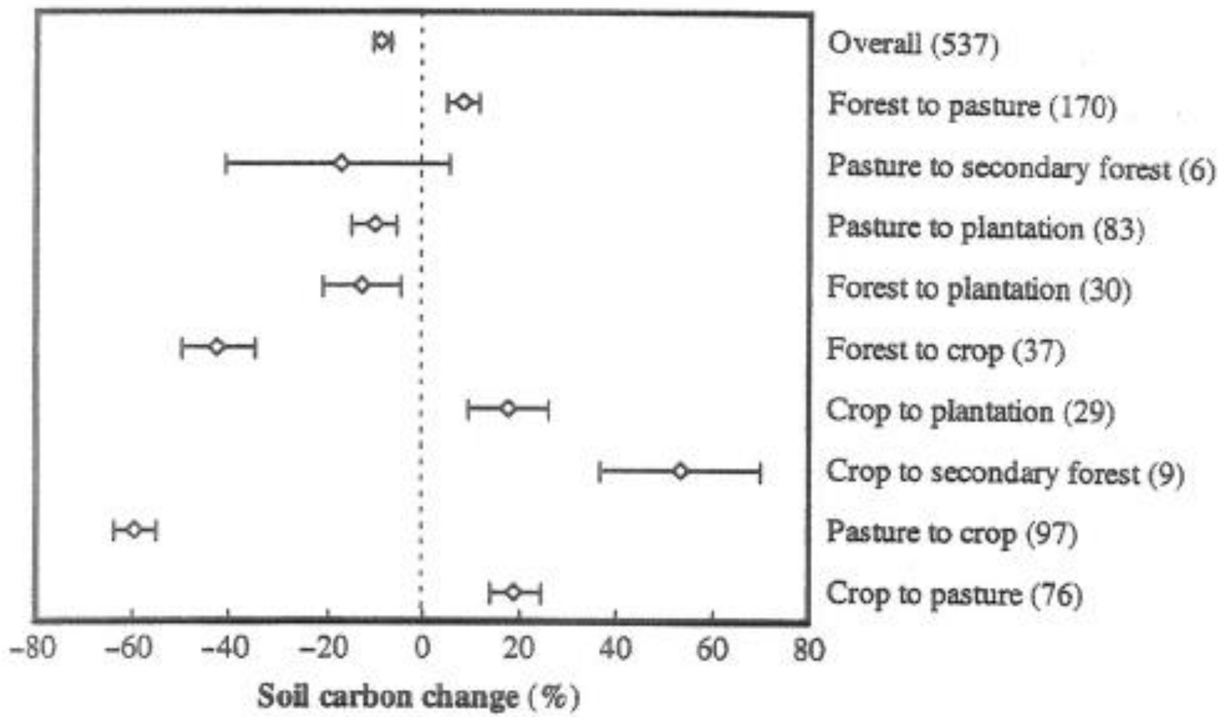
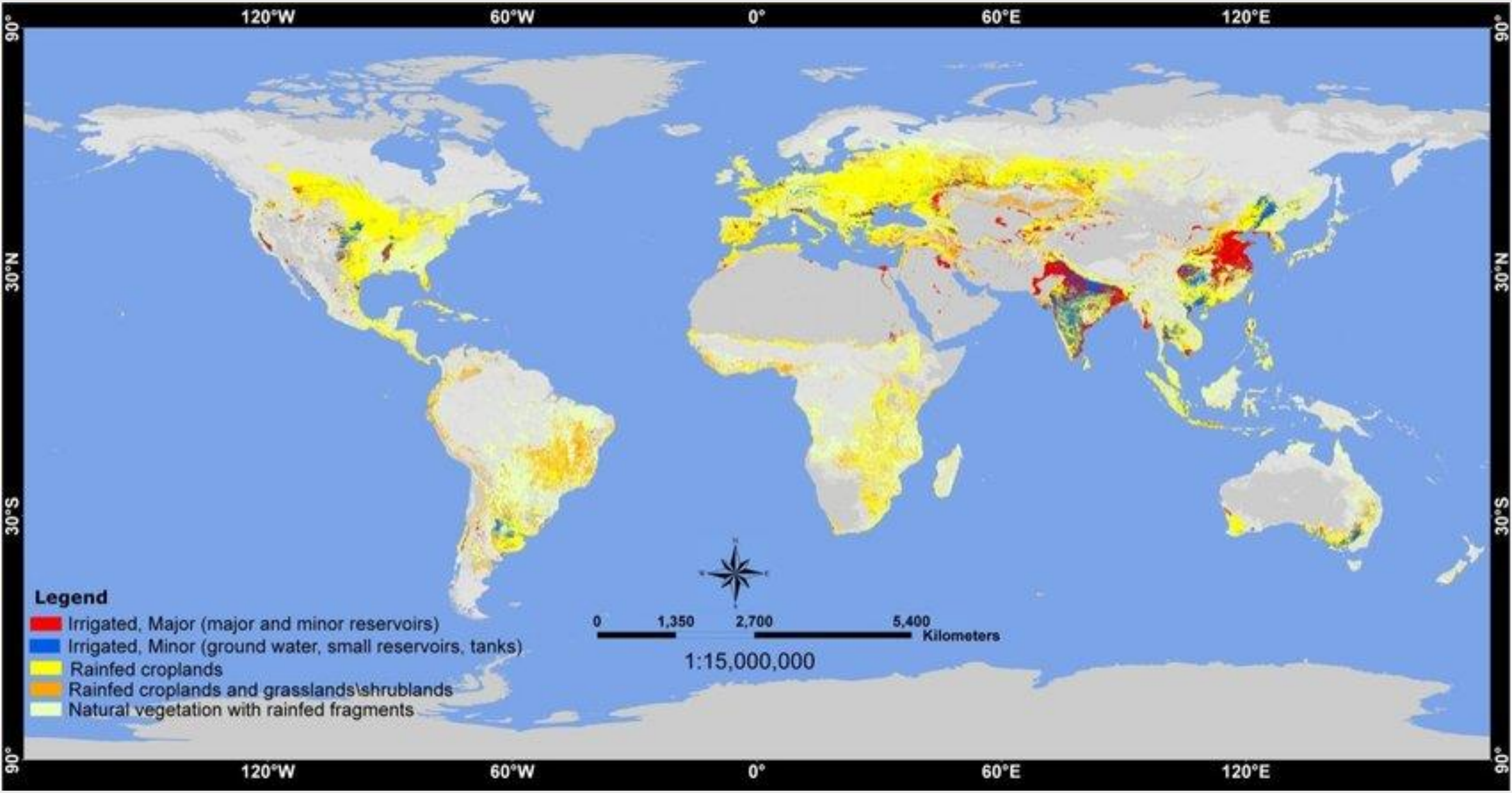


Fig. 1 Soil carbon response to various land use changes (95% confidence intervals are shown and numbers of observations are in parentheses).

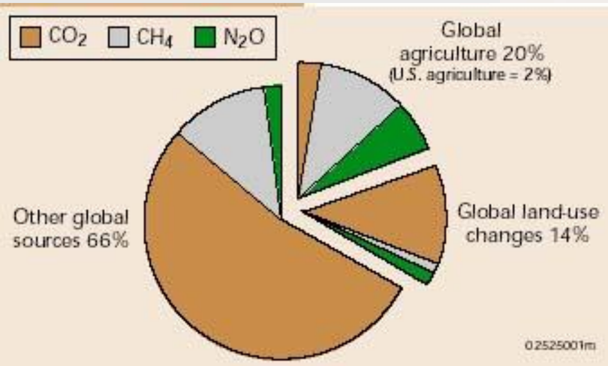
Low C stocks in agricultural soils : why ? Can we reverse it ?

Global cropland map

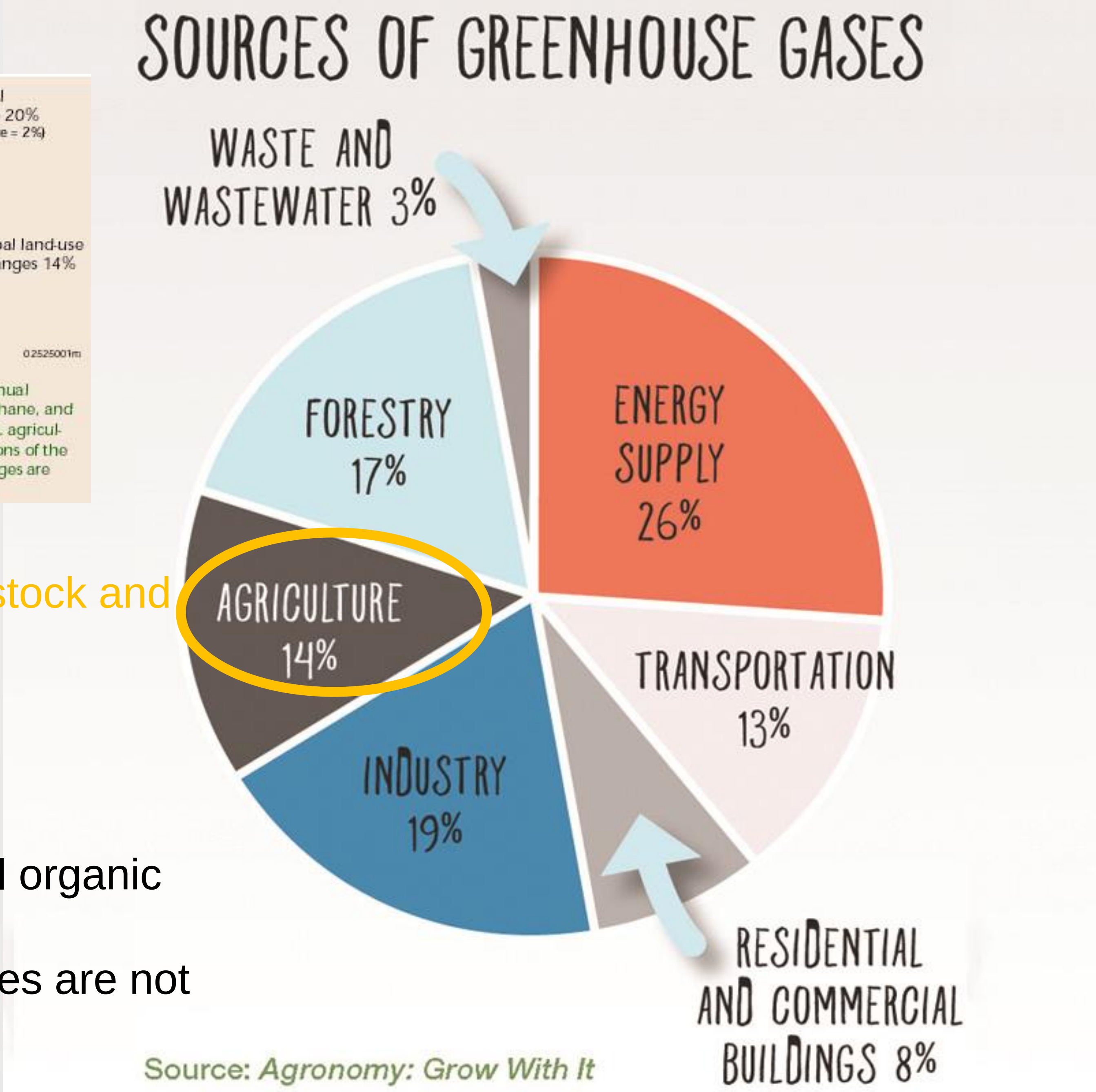
Thenkabail et al. (2010)



Approx. 12% of land surface area ➔ main cause of land use change



Summary Graphic A: Percent contributions to the annual increase in the greenhouse gases carbon dioxide, methane, and nitrous oxide, based on global warming potential. U.S. agriculture emissions are 2% of the carbon equivalent emissions of the three greenhouse gases shown. Global land-use changes are agriculture related. Source: IPCC 1996.



Emissions from livestock and management

But changes in soil organic carbon stocks and albedo/energy fluxes are not accounted for

Why are we interested in field crops?

- Cultivated areas represent 1/3 of Europe's land mass and 11.6% of continental areas in 2007 (source FAOStat).

- Strong socio-economic issues: food production, survival of the agricultural sector, landscape issues, etc.

- Sensitive to climate hazards (problematic in a context of climate change)

- The increase in agricultural areas in recent centuries has altered the land surface: effects on runoff/drainage/evaporation of water (climate effects), on the surface albedo (fraction of solar energy reflected from the surface) which first determines the amount of energy on the earth's surface and in the atmosphere (greenhouse effect) and other biophysical parameters (roughness, etc.)

- Agriculture also contributes about 14% of the world's GHG emissions but high uncertainty regarding the GHG emissions of cultivated plots: especially concerning the variations of C stocks in the soil!!

- Low C stocks in agricultural soils (low organic matter = less fertile) ➔ high potential for capturing atmospheric CO_2 for sequestration in soil organic matter (reduction of greenhouse effect and soil improvement).

-Other levers for climate mitigation than CO_2 sequestration and reduction in GHGs emissions ?

Some key questions

What is the share of lateral/vertical fluxes in energy, water, carbon and GHG budgets?

- **Vertical fluxes:** albédo, CO_2, N_2O, CH_4…
- **Lateral fluxes:** imports, exports de C, irrigation, ruissellement…
- **GHG emissions from parcel management?**

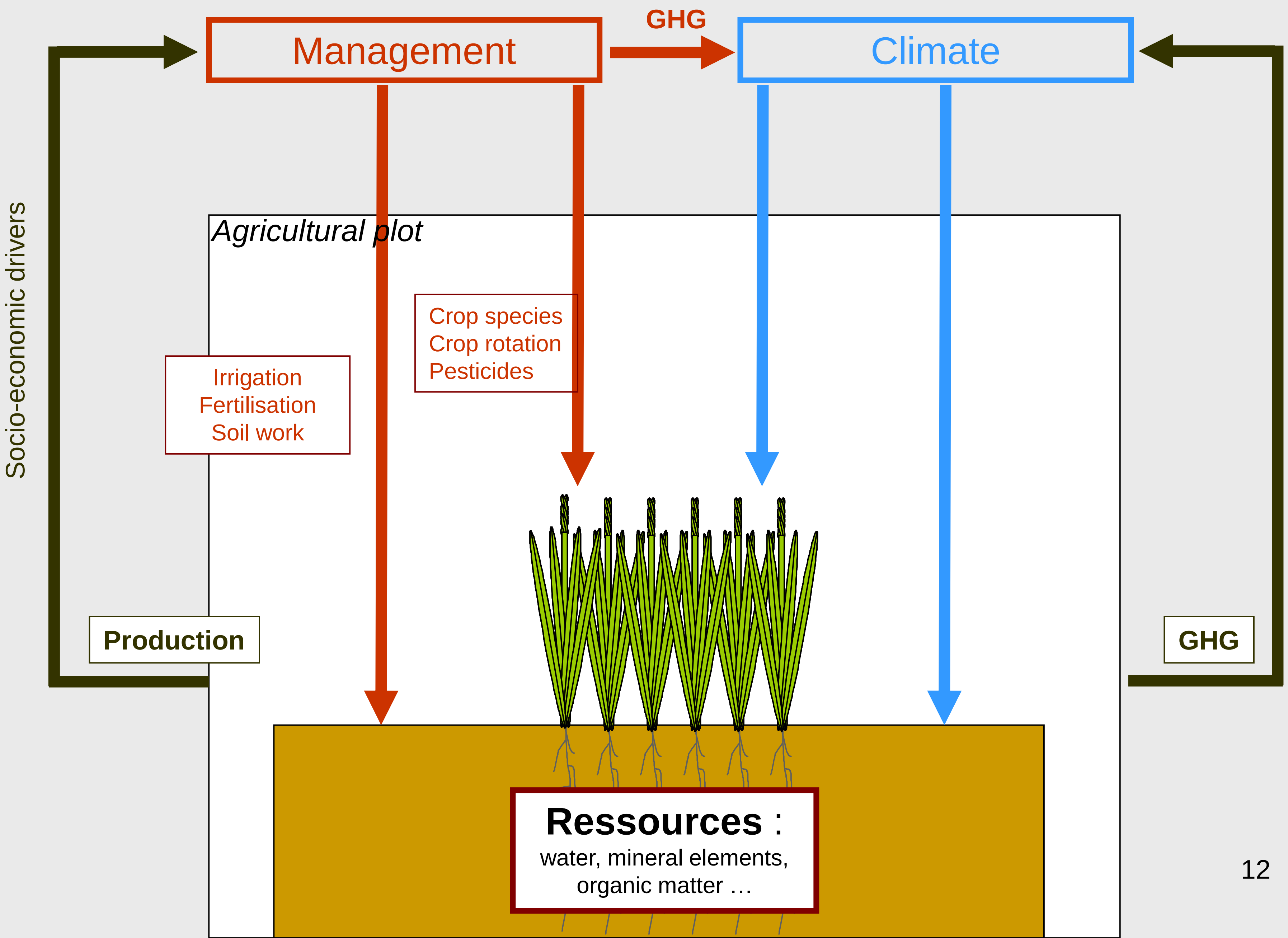
How can we quantify the influence of the main factors controlling these fluxes and budgets at different spatial scales?

- **Biotic factors: vegetation dynamics, soil microorganisms**
- **Abiotic factors: climate, soil**
- **Anthropogenic factors: crop rotation, cultural practices, etc.**

What are the levers to:

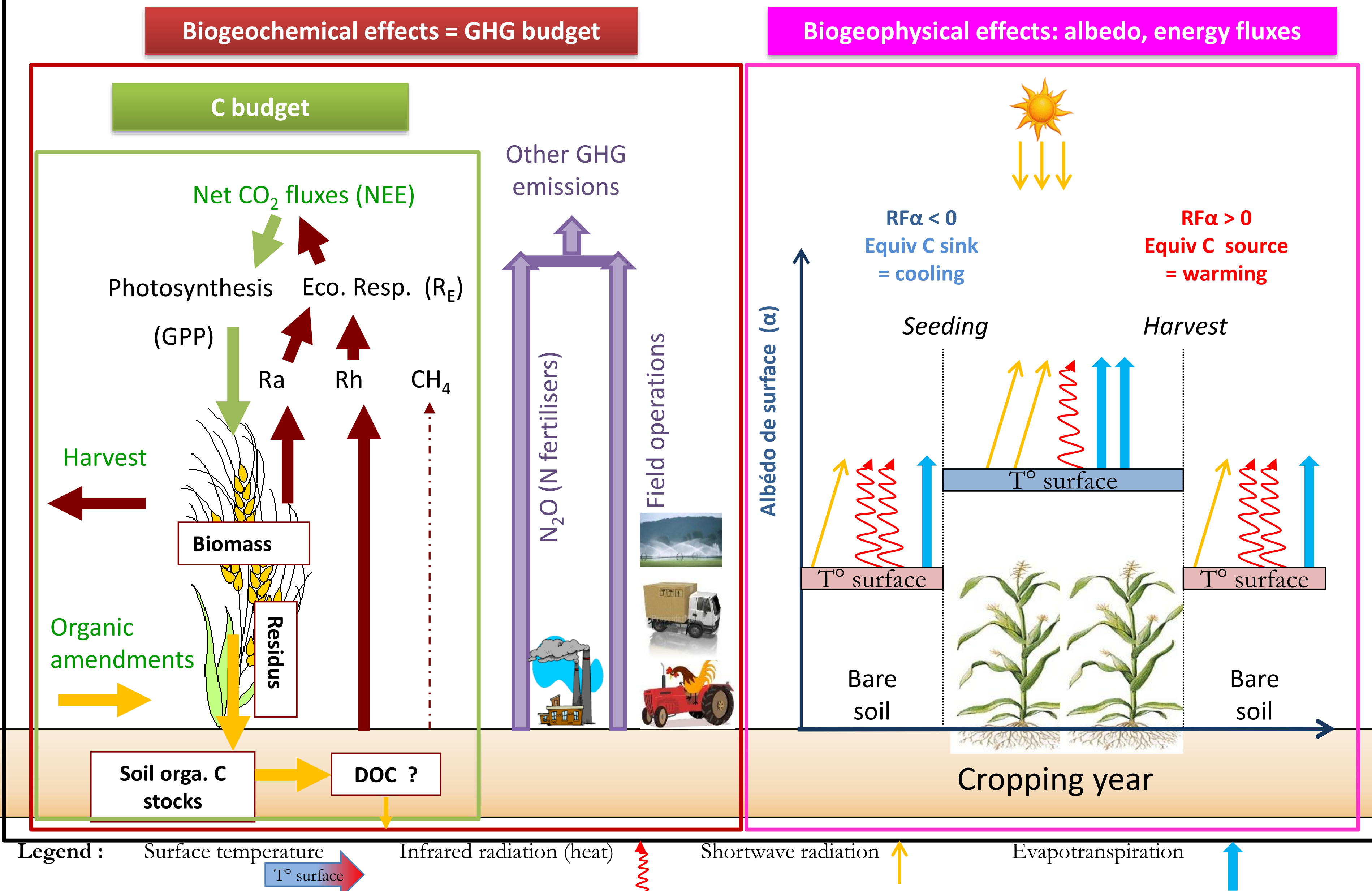
- **maintain good production levels and significantly reduce GHG emissions, or even re-store C in soils?**
- **reduce the share of cropland in the earth radiative forcing?**
- **improve the water use efficiency of agro-ecosystems?**
- **what criteria should be taken into account?**

System studied: the agricultural plot



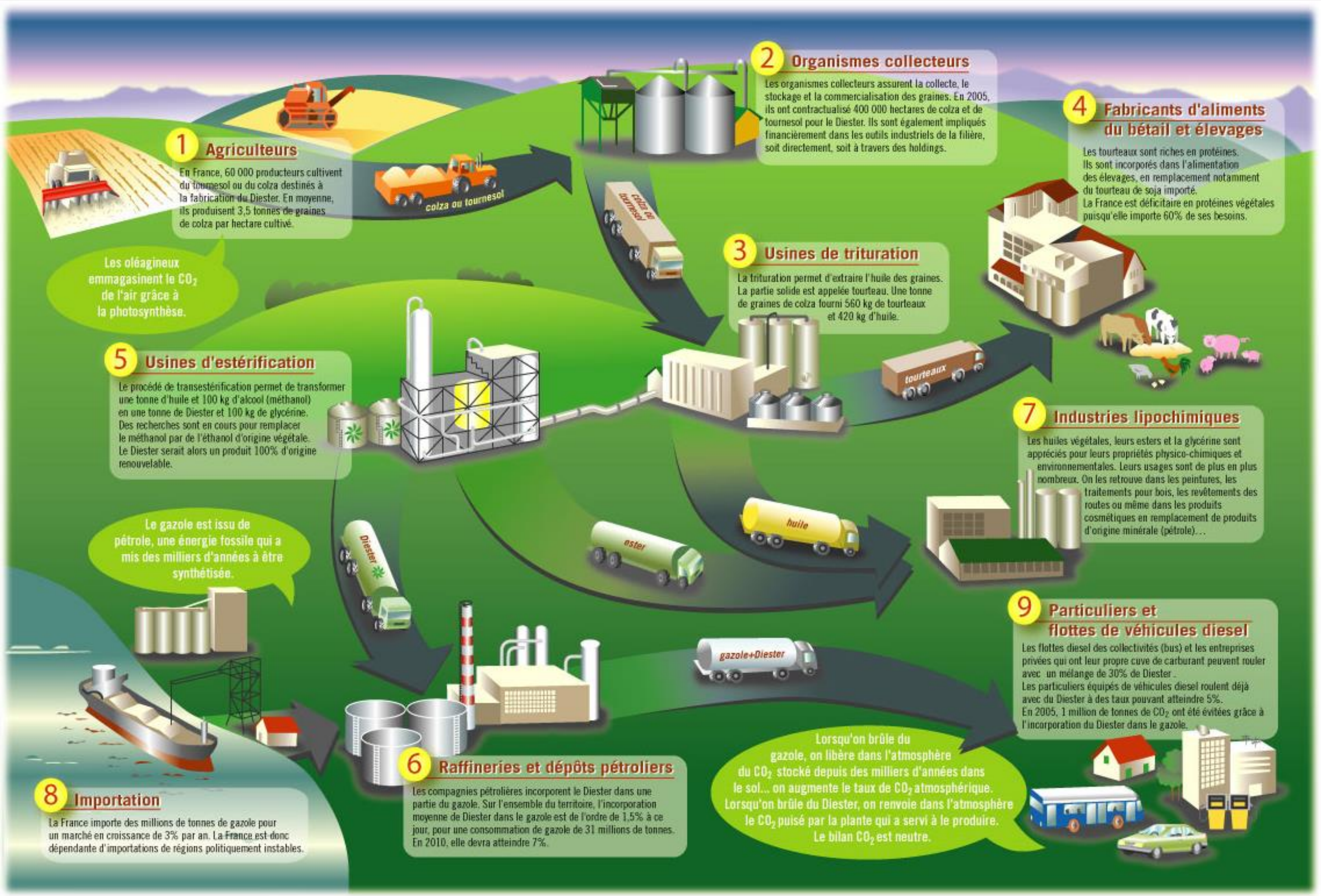
Effect of crops on climate

Radiative forcing (in C of CO_2-eq) = (C budget + N_2O + FO) + (albedo effect + Δ H/ET)

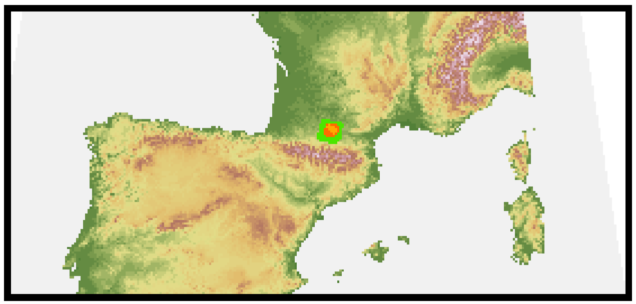


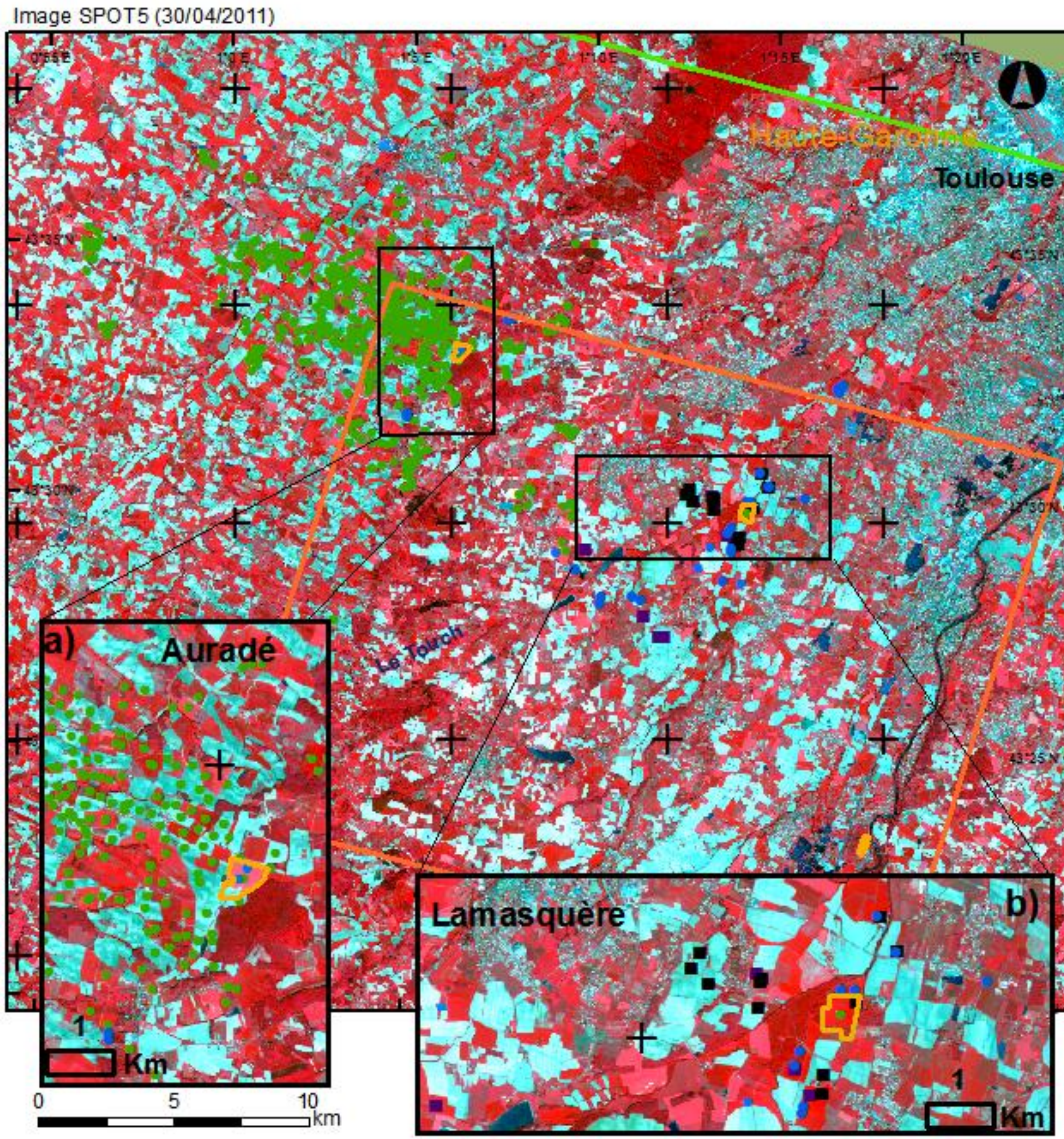
No accounting of the fate of harvest in the GHG budget

First approximation: everything goes back into the atmosphere



Case study: the Regional Space Observatory (France)





Experimental Sites (2004...)

ESU — Biomass & Yield Data (2011)

Yield Data (farmers surveys)

ESU — LAI & Biomass Data (2008)

LAI & Biomass Data (2010)

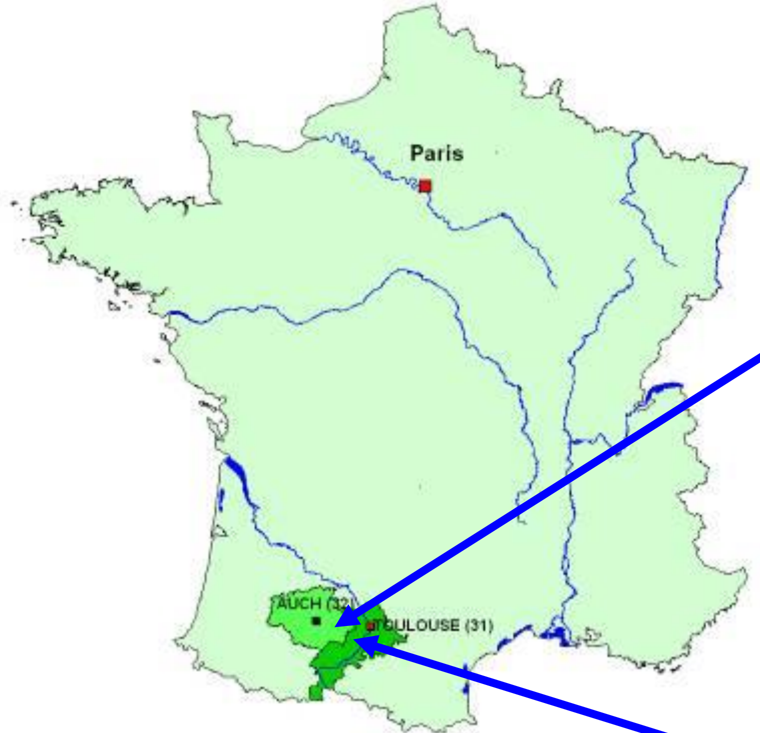
SAFRAN grid

SPOT window (depuis 2002)

Formosat-2 window (depuis 2006)

Flux sites in South Ouest France

Analysing C & GHG budgets by using flux towers allows a dynamic understanding of the processes (vs soil sampling every 5 yr)



Auradé (Gers, 32)

Lamasquère (Haute Garonne, 31)

- Same instrumental setup
- Part of international flux sites networks (e.g. ICOS)
- Distant by only 12 km
- Differences in soil & management

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Auradé (Gers, 32)

Altitude : **245 m**

Surface : **23.5 ha**

Slope : **2 %**

Soil : **Luvisol (hills)**

Temperatures : **13.5 °C**

Precipitations : **680 mm**

Management : **mineral fertilisation**

Lamasquère (Haute Garonne, 31)

Altitude : **180 m**

Surface : **32.3 ha**

Slope : **0 %**

Soil : **Luvisol on alluvial deposits (valley)**

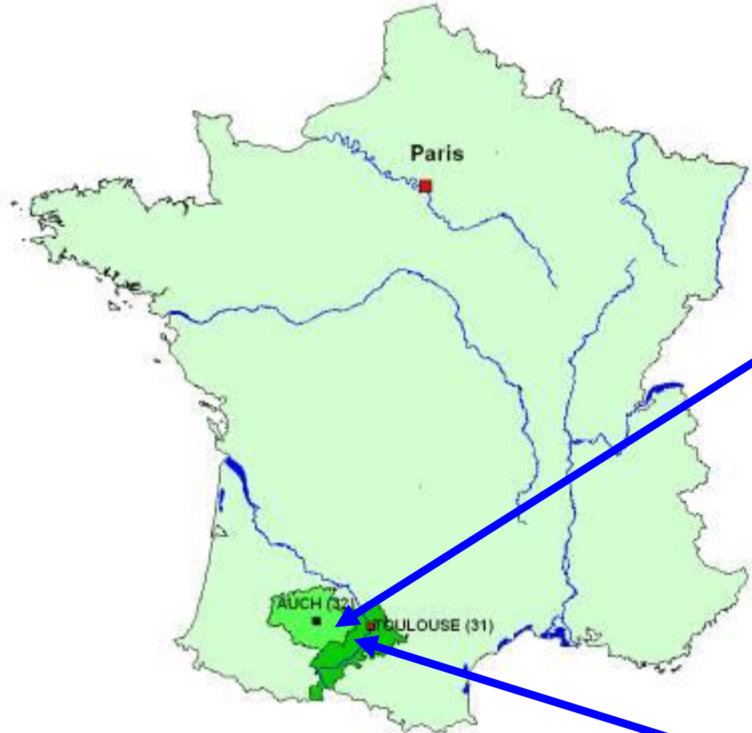
Temperatures : **13.3 °C**

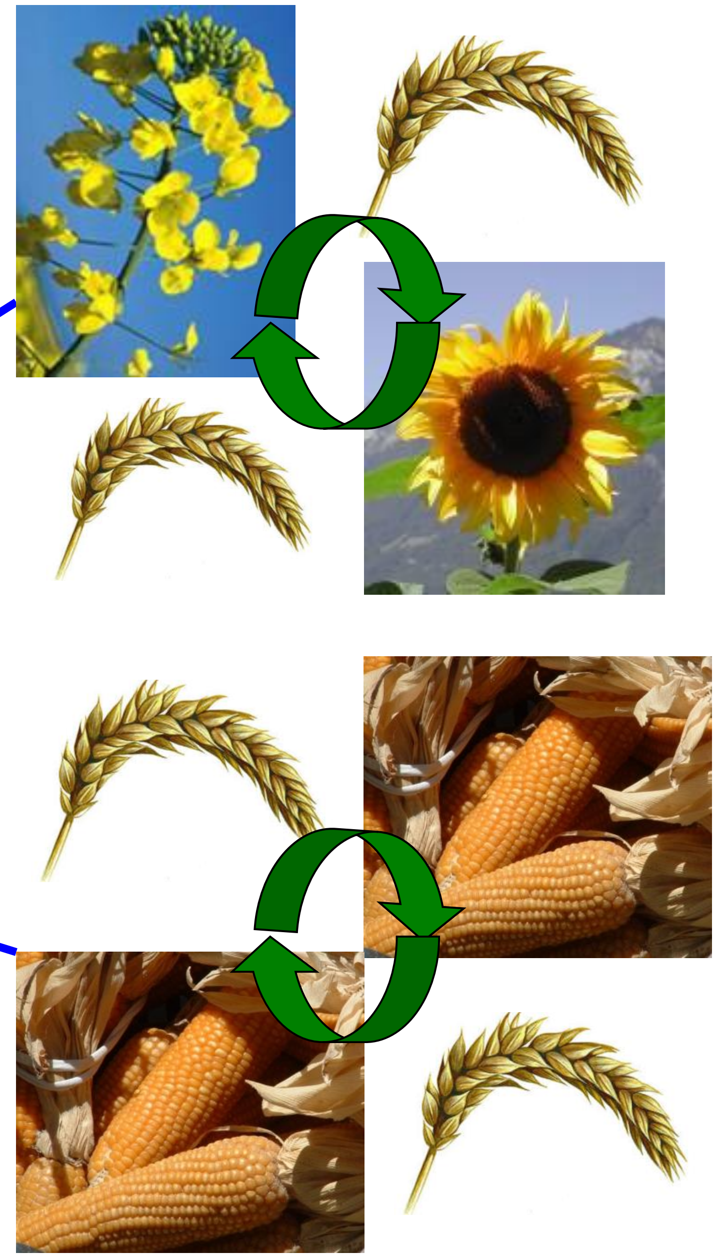
Precipitations : **651 mm**

Management : **mineral & organic fertilisation, irrigation**

Flux sites in South Ouest France

Analysing C & GHG budgets by using flux towers allows a dynamic understanding of the processes (vs soil sampling every 5 yr)





- Same instrumental setup
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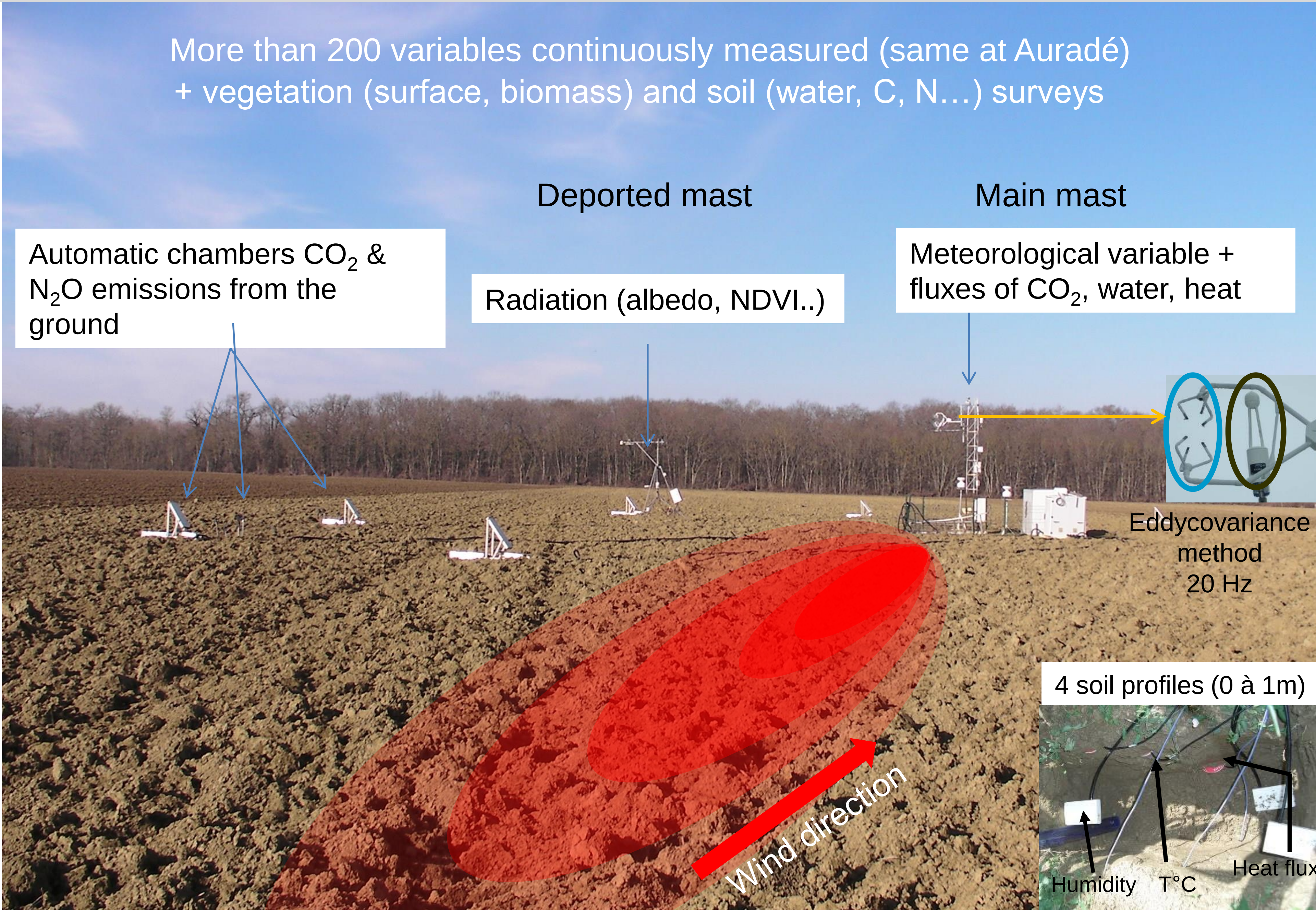
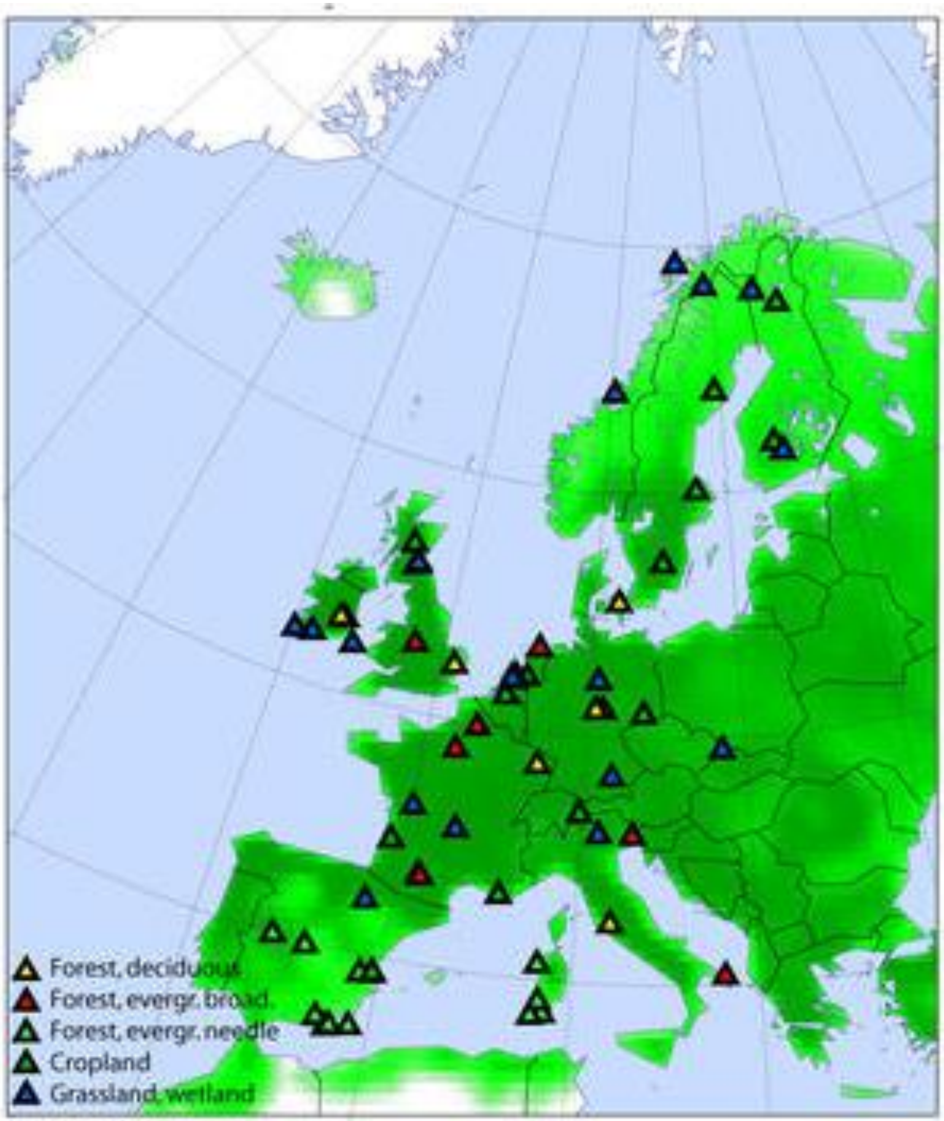
The Lamasquère flux site



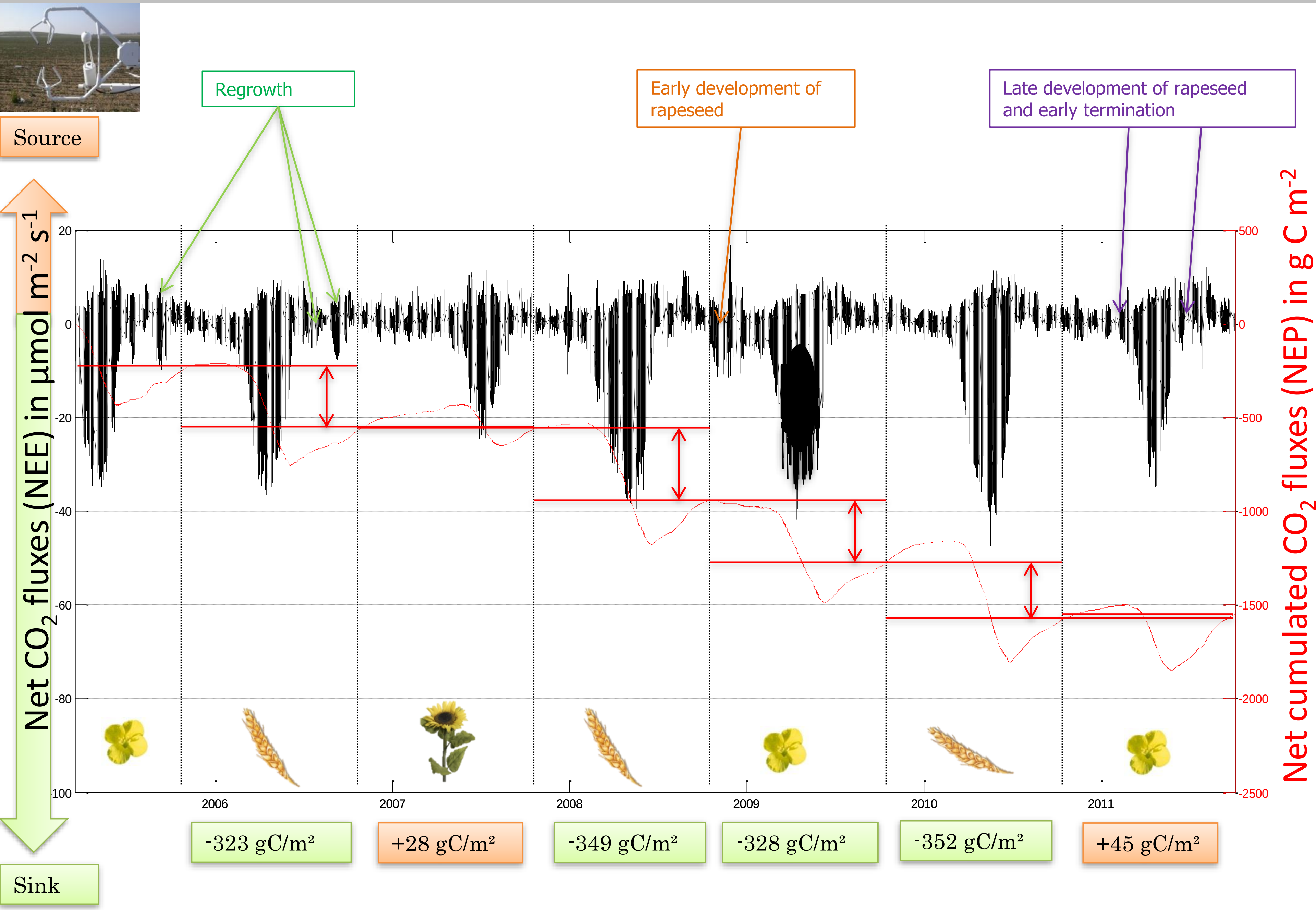
Similar sites in Europe (ICOS network)



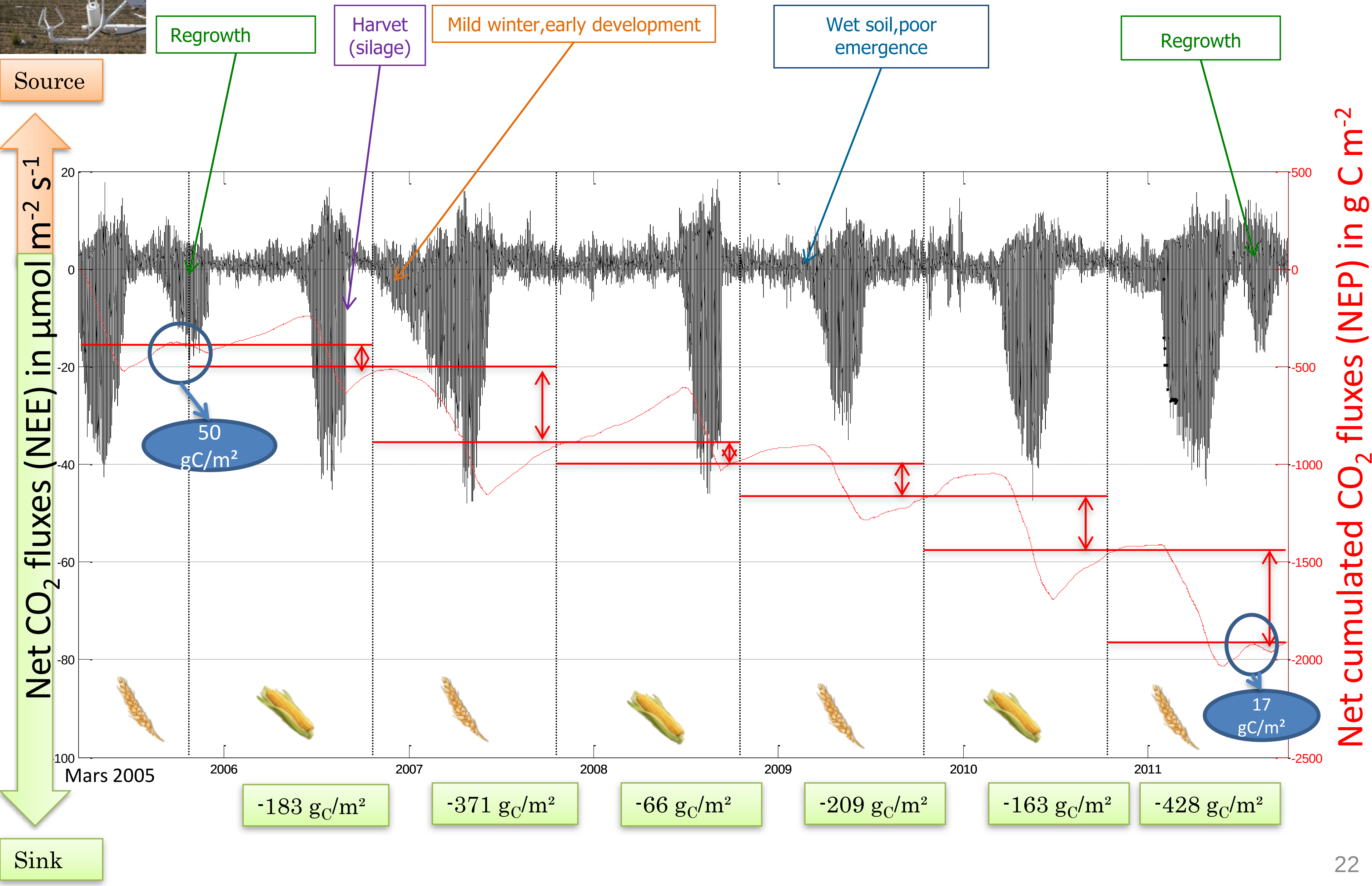
Ecosystem network

- Approx 15 towers on cropland
- More than 20 crops species studied
- Large range of pedoclimates and management practices

Exchanges of CO_2 parcel/atmosphere at Auradé

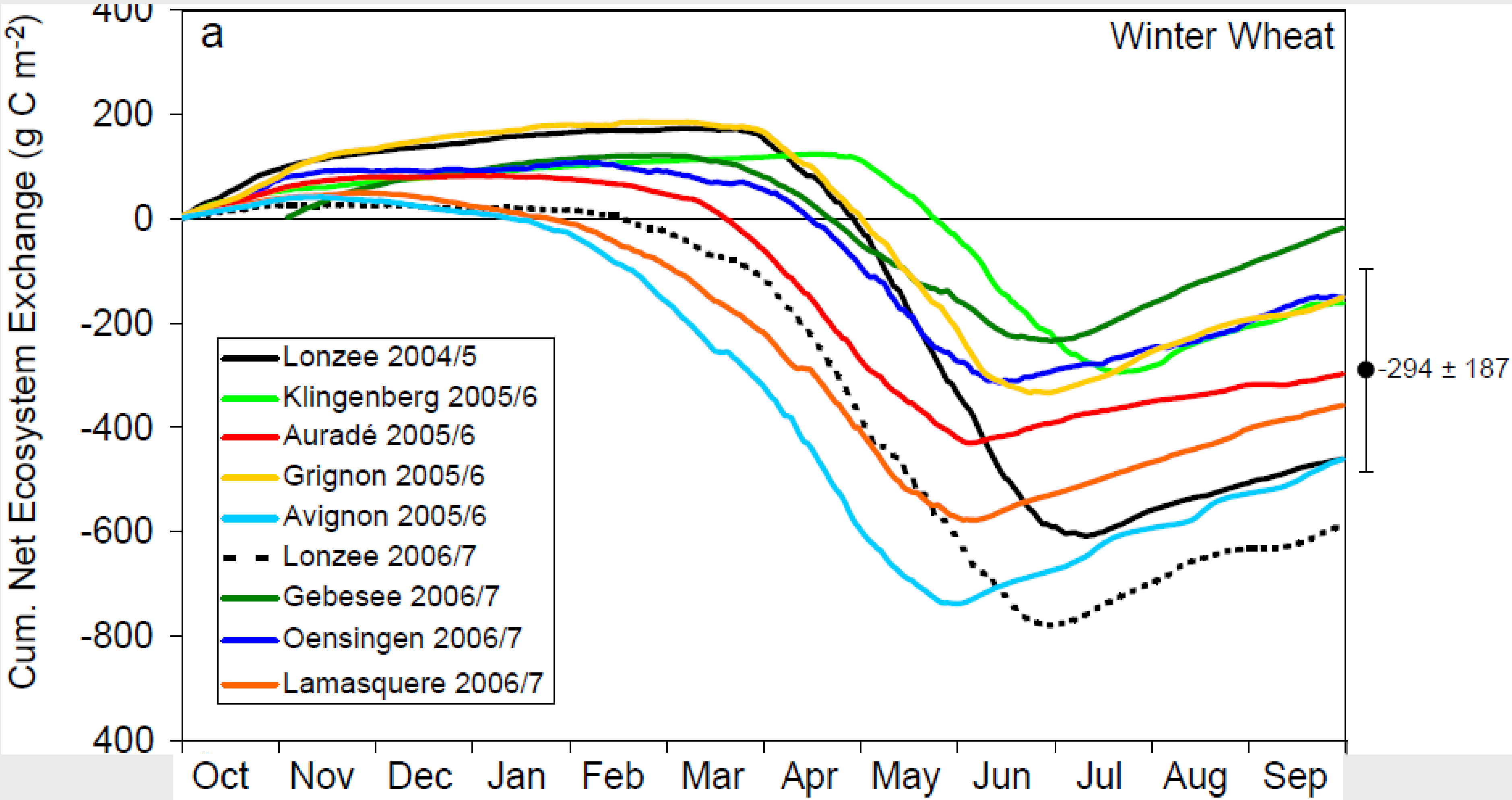


Exchanges of CO_2 parcel/atmosphère at Lamasquère



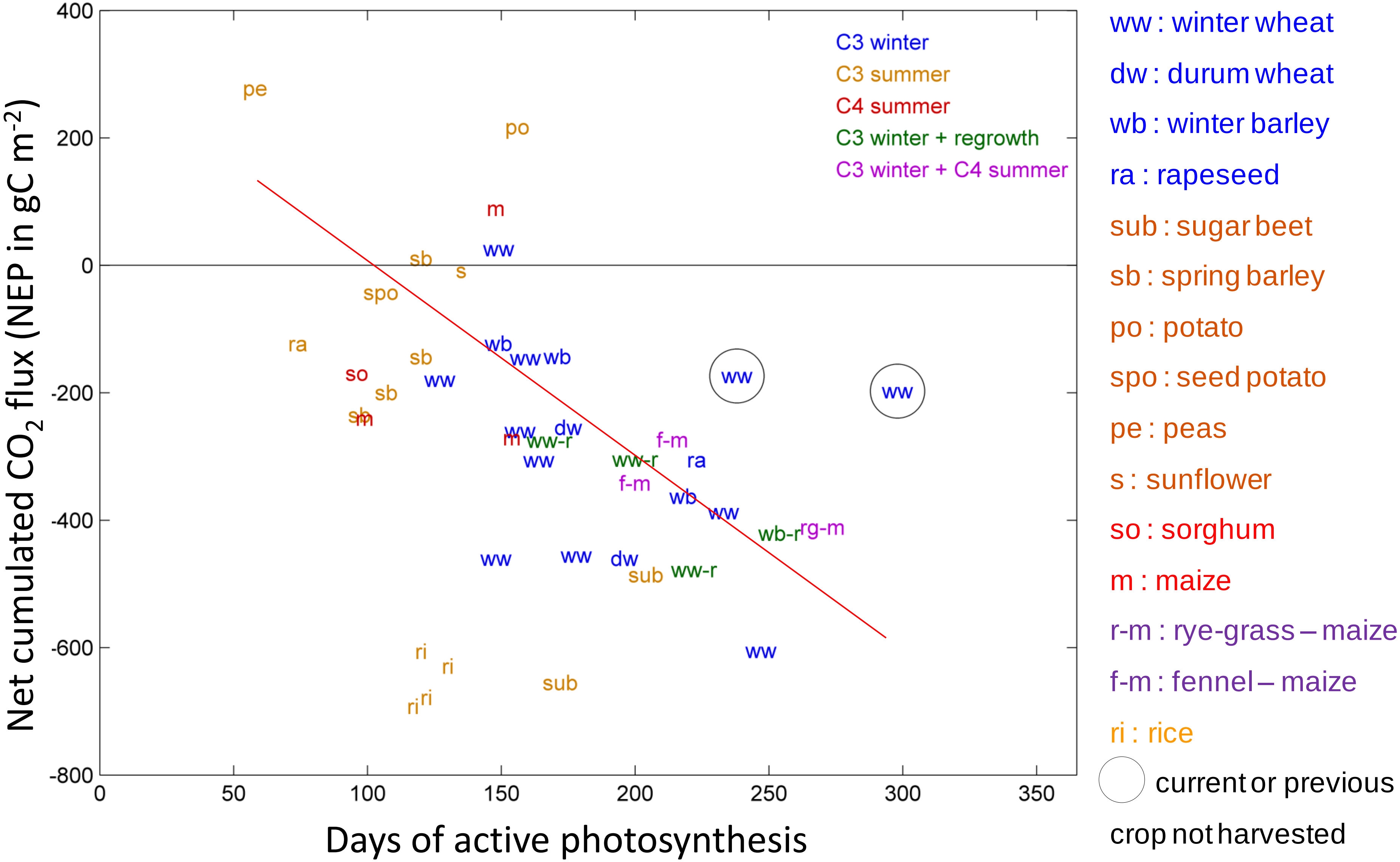
Annual dynamics of CO_2 fluxes for winter wheat

(Kutsch et al. 2010)



Net cumulated CO_2 flux and growing season length

Ceschia et al. (2010) in AEE



The longer the growing season, the greater the annual net CO_2 fixation

Annual CO_2 flux mapping

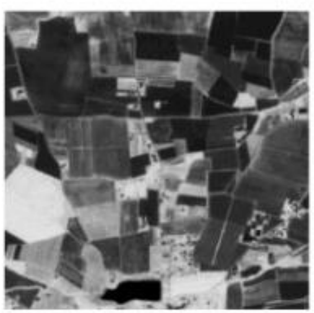
Empirical approach ➔ most crop species except rice

Open source code https://gitlab.com/nivaeu/uc1b_indicators_tool

IACS (LPIS + GSAA)

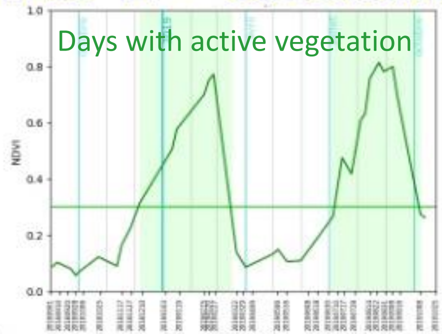
(vector)

Sentinel-2 Images

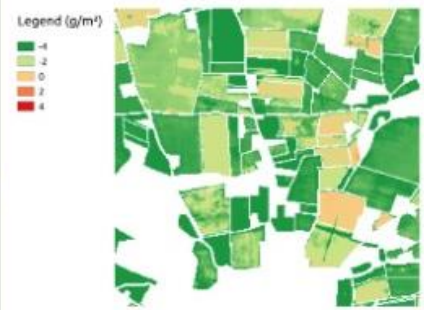


(raster)

Tier 1 - Calculator

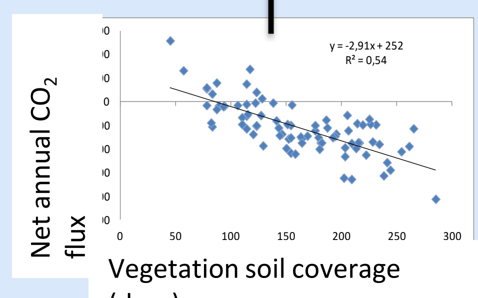


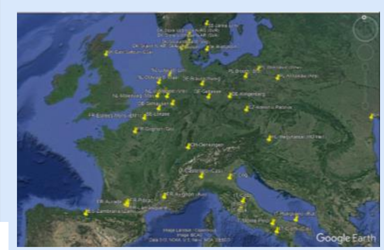
Tier 1
Net Annual CO2 Flux



(vector & raster)

Based on Ceschia et al. (2010)





Cropland sites flux tower

Net annual CO_2 flux depends on the total number of days with active vegetation covering the soil

Annual CO_2 flux mapping

NIVA'S algorithm + Iota2 software

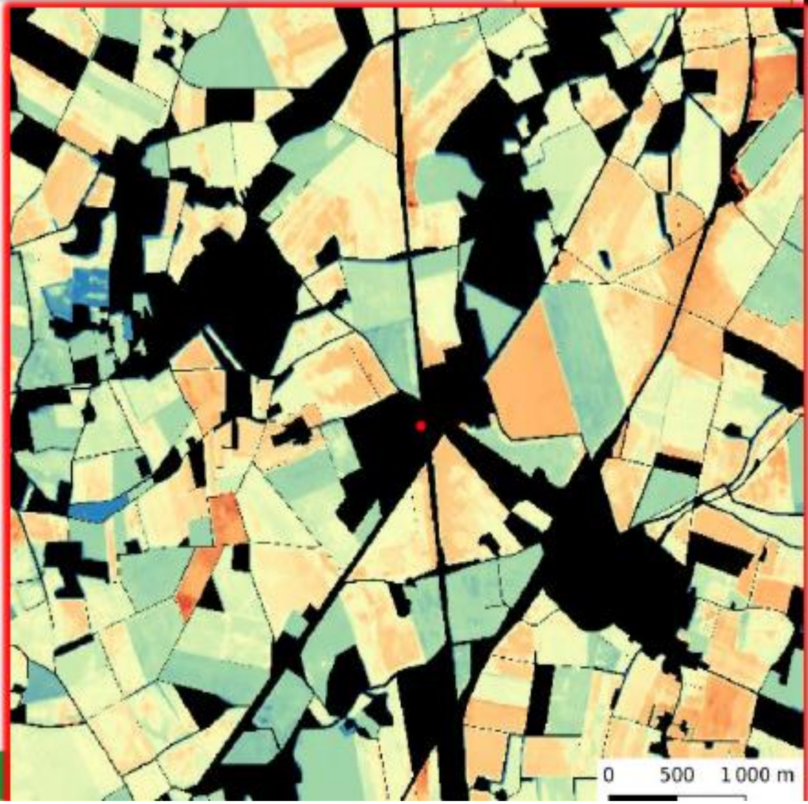
With the support of cnes

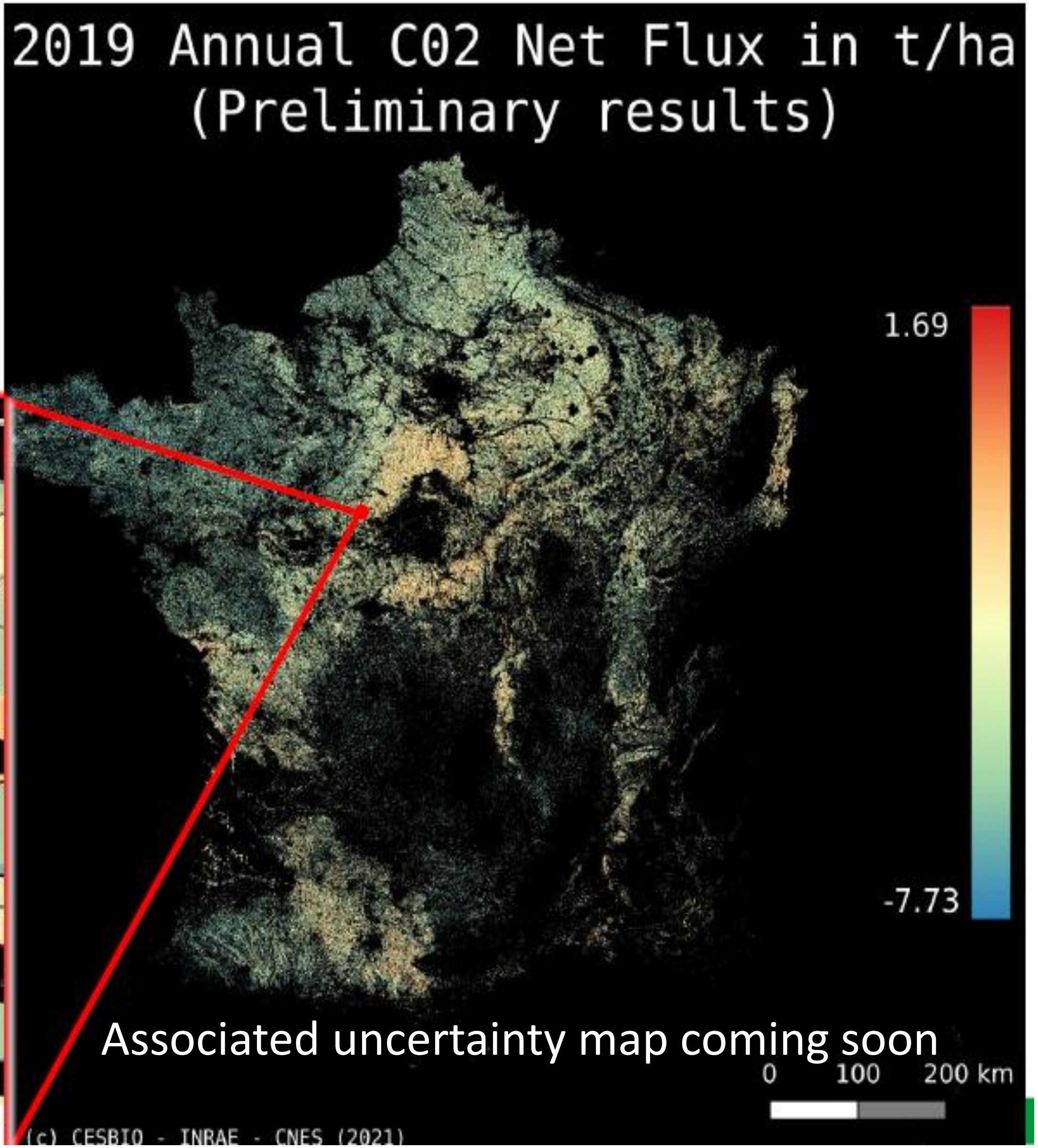
Annual CO_2 fixation

Annual CO_2 losses

All crops except rice

France = 94 Sentinel-2 tiles



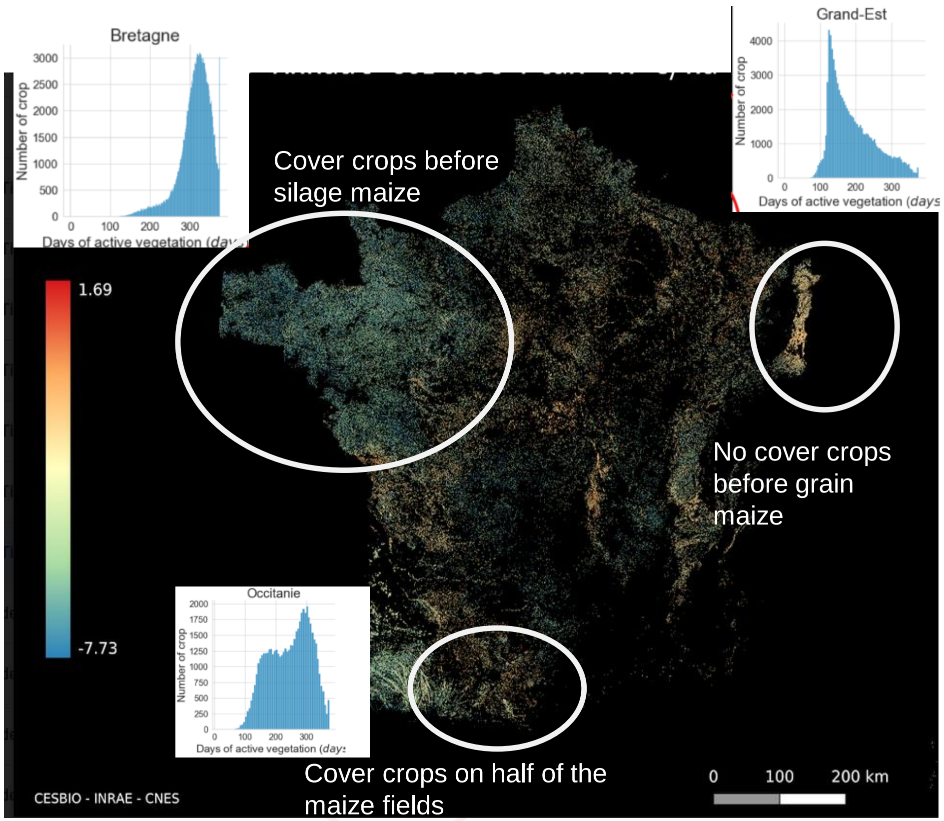


Associated uncertainty map coming soon

Link between maize type and duration of soil coverage

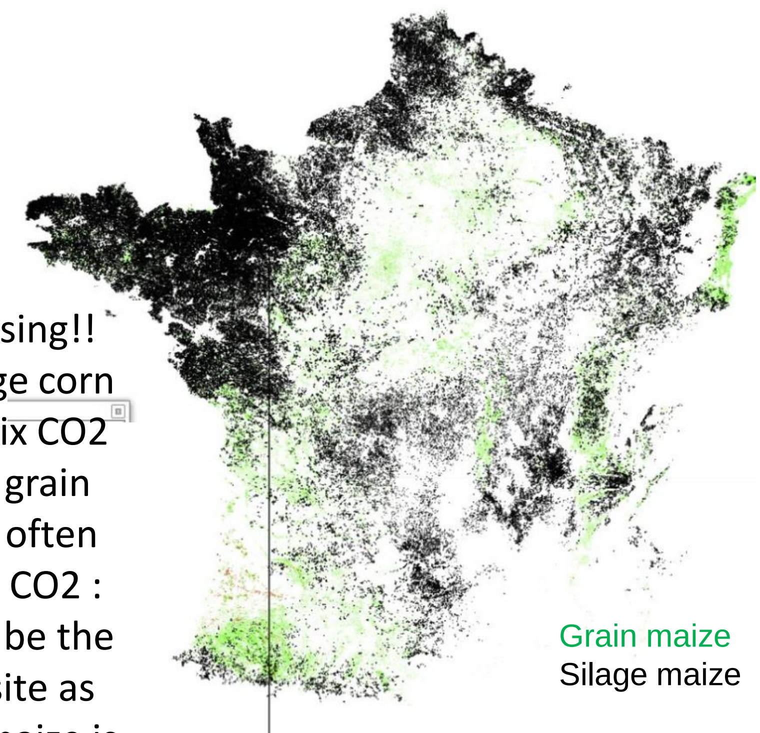
Effect of practices (type of harvest, plant cover) and regulations (Nitrates Directive)

Flux nets annuels de CO_2 sur les parcelles de maïs en France en 2019



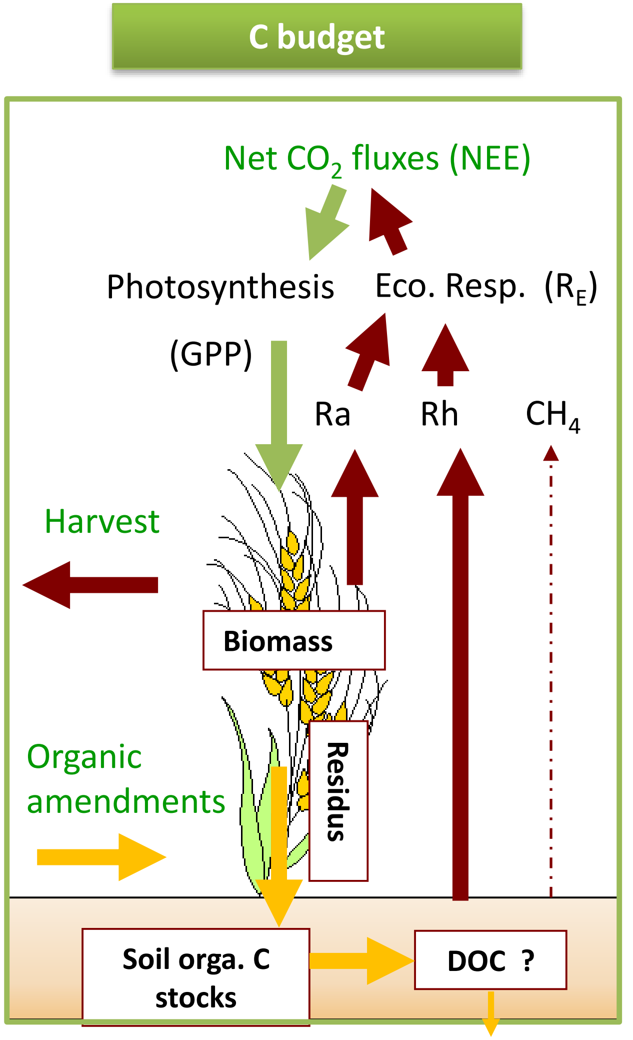
Surprising!! All silage corn areas fix CO2 while grain maize often looses CO2 : should be the opposite as silage maize is harvested earlier

Types de maïs (données RPG)



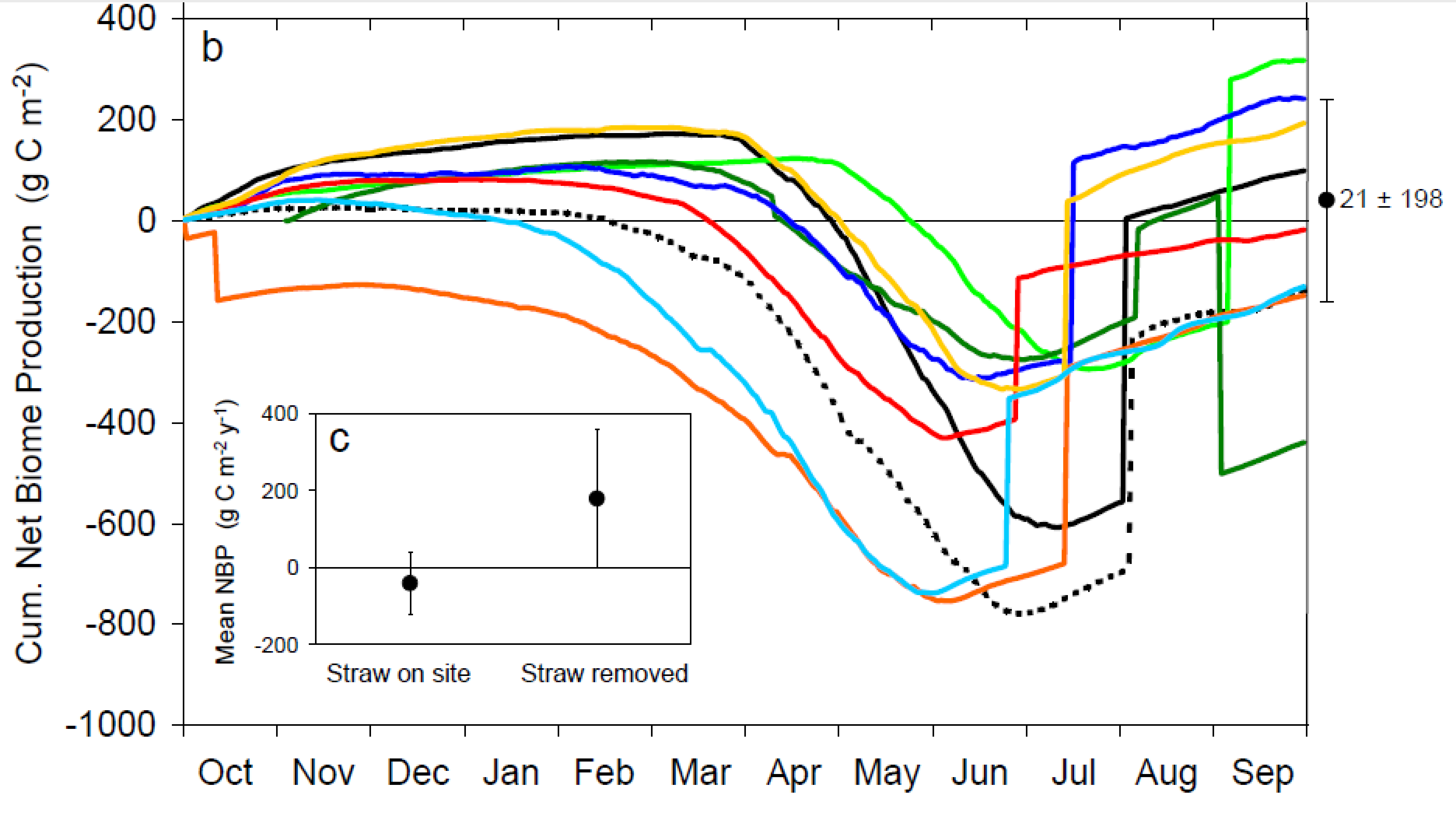
Grain maize
Silage maize

Interesting but CO_2 fluxes are only one component of the C & GHG budgets…



Carbon budget of winter wheat plots in Europe

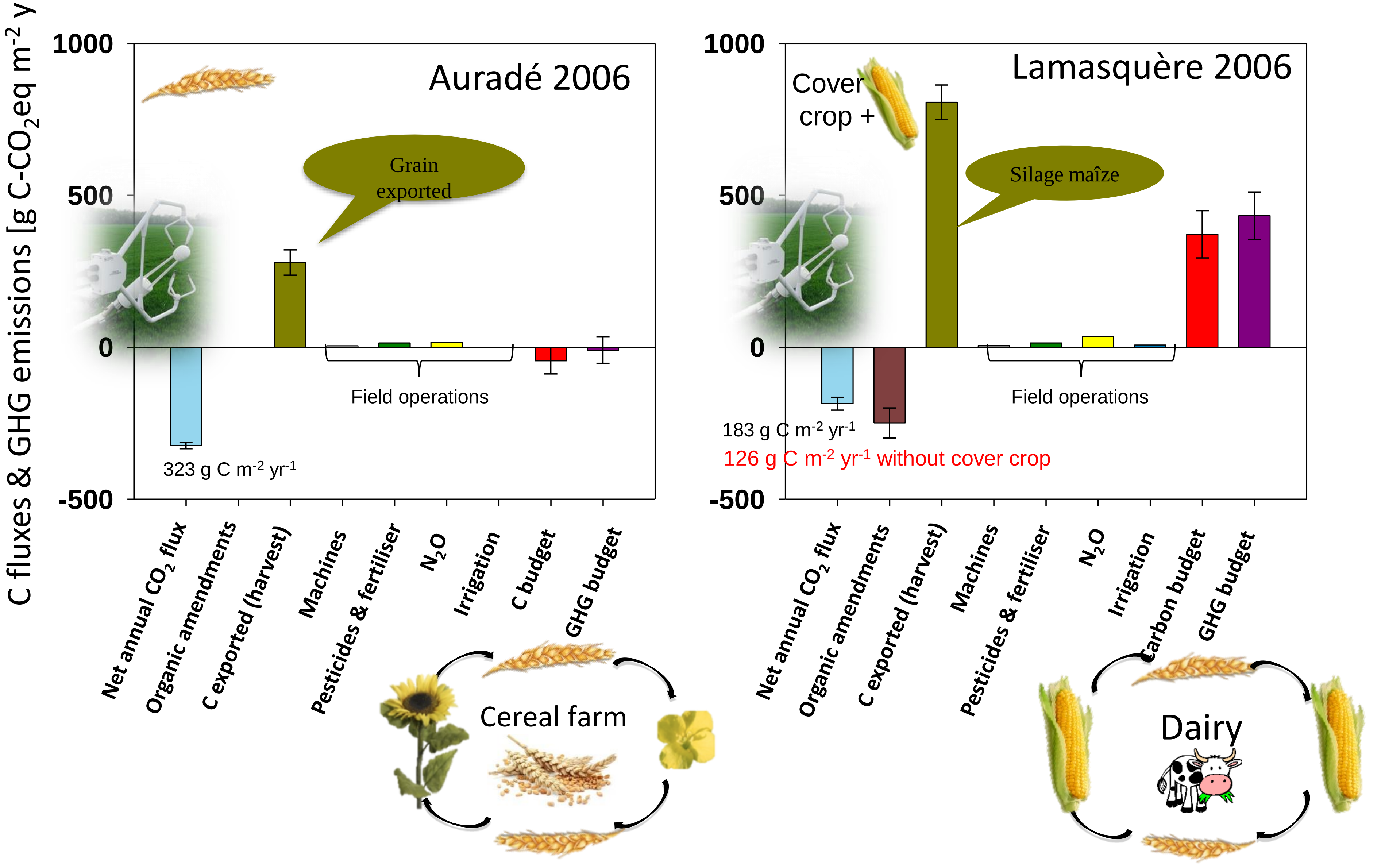
(Kutsch et al. 2010)



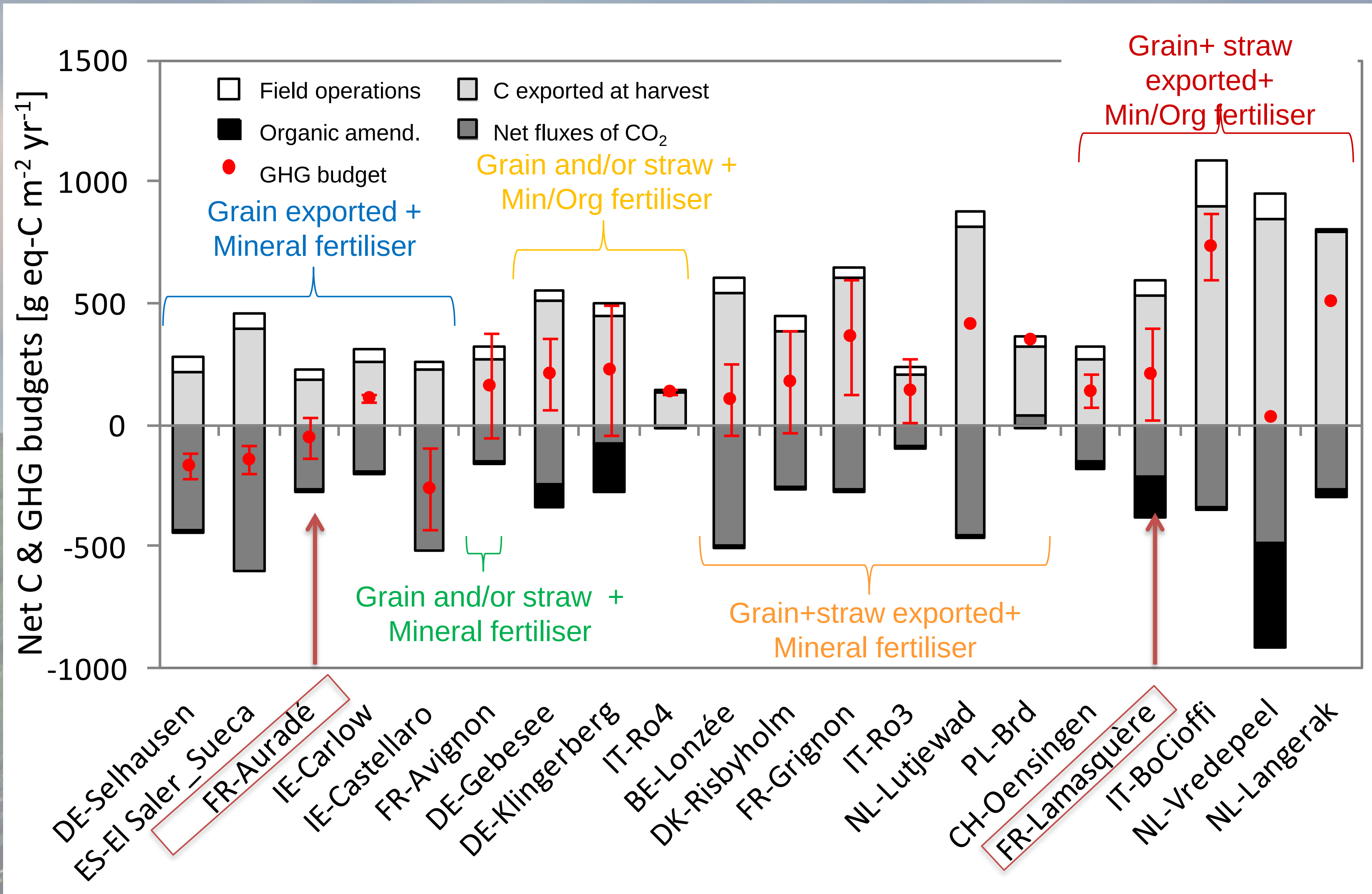
Do not export straws ! Leave them on the ground or incroporate them in the soil

Exemple of C & GHG budgets (+ uncertainties)

See Ceschia et al. (2010) in AGEE



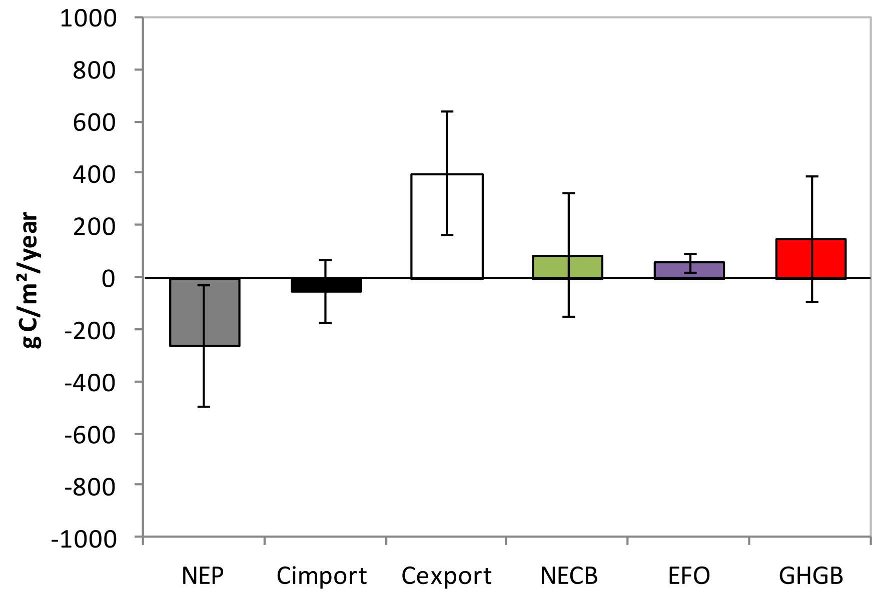
GHG budgets at flux sites in Europe

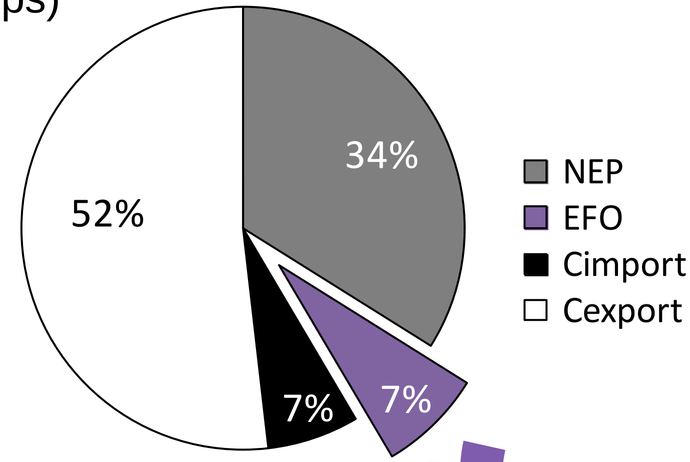


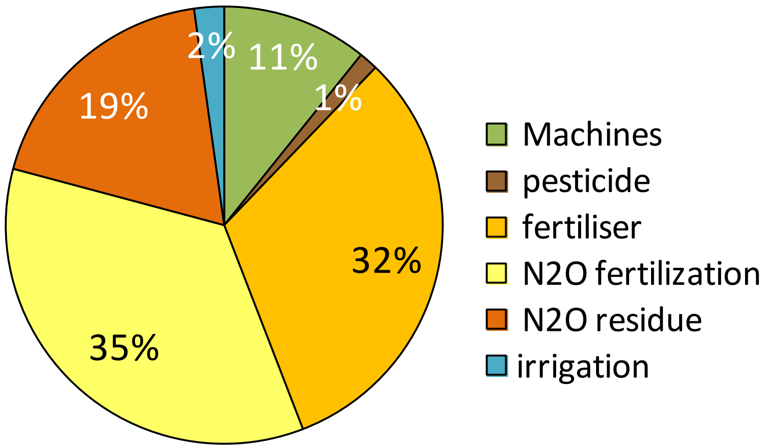
C & GHG budgets at European flux sites (+ uncertainties)

Without changing the production, it is mainly by acting on the C budget components that the C & GHG budgets can be improved:

- 1) reduce bare soil periods to fix more CO_2 (increase NEP term) ➔ cover crops
- 2) organic amendments (but limited ressource)
- 3) Straw should be returned to the soil
- 4) for N_20, reduce mineral fertilisation (precision farming, leguminous cover crops)







Conclusions concerning the levers to improve the GHG budgets of cropland based on in-situ data

•Technical operations account for a small share of GHG emissions from plots ➔ mainly through N_2O emissions related to the degradation of N fertilizers & fertilizer manufacturing ➔ reduce the use of mineral fertilisers by using leguminous cover crops

•C exports at harvest represent the main contribution to GHG emissions but cannot be reduced without changing the production (= farmers' income and our food regime)

•It is therefore on the net fluxes of CO_2 that we must act in priority ➔ increase the CO_2 fixation by limiting the periods of bare soil (e.g. cover crops, changes in crop rotation, introduce temporary grasslands)

Conclusion of the national expertise on how to store more C in French soils

Pellerin et al. (2019) using the STICS crop & grassland model

	Additional C storage 0-30 cm soil layer	Potential applicability	Potential additional C storage at the national level 0-30 cm soil layer	Relative yearly increase of soil C stocks (=949 Mt C for cropland soils in mainland France)
	Kg C/ha/an	Mha	Mt C/year	‰ /year
Arable cropping systems				
Expansion of cover crops	+126	16.03	+2.019	
No tillage	+60	11.29	+0.677	
New carbon inputs	+61	4.21	+0.257	
Expansion of temporary grasslands	+114	6.63	+0.756	
Agroforestry	+207	5.33	+1.102	
Hedges	+17	8.83	+0.150	
Total for croplands			+4.960	+5.2 ‰

The reference for the cover crop extension scenario already contains cover crops. Based on a bare soil reference the additional storage is 313± 313 Kg C/ha/year (instead of 126 Kg C/ha/year)

Conclusion of the national expertise on how to store more C in French soils

Pellerin et al. (2019)

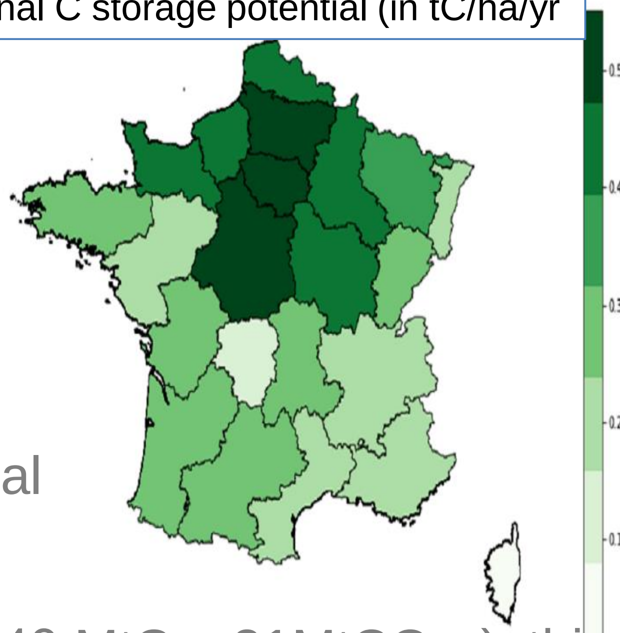
	Additional C storage Horizon 0-30 cm	Potential applicability	Potential additional C storage at the national level Horizon 0-30 cm	Relative yearly increase of the soil C stock
	Kg C/ha/year	Mha	Mt C/year	‰ /year
Permanent grasslands				
Moderate intensification of extensive grasslands	+176	3.94	+0.694	
Grazing instead of mowing	+265	0.09	+0.023	
Total for permanent grasslands			+0.720	+0.9 ‰
Vineyard				
Grass cover	+182	0,56	+0.103	
Total for vineyard			+0.103	+3.7 ‰

!!! Organic C storage capacity limited in time ➔ new equilibrium reached after 50 years!!! Above need to preserve the existing stocks (meadows, bogs, forests)

Conclusion of the national expertise on how to store more C in French soils

Pellerin et al. (2019)

- A potential for additional C storage of about 5.78 Mt C/year (in the 0-30cm soil layer)



- This represents an annual increase of
  - +5,2 ‰ for croplands
  - +0,9 ‰ for grasslands
  - +3,3 ‰ for all agricultural soils
- This potential is mainly found in arable soils (86% of the total potential), partly because initial soil C stocks are low
- Extrapolated to the whole soil profile (5,78 → 8,43 MtC = 31MtCO_2e), this additional C storage would compensate 6,8% of national GHG emissions (458 MtCO_2e)

Questions:

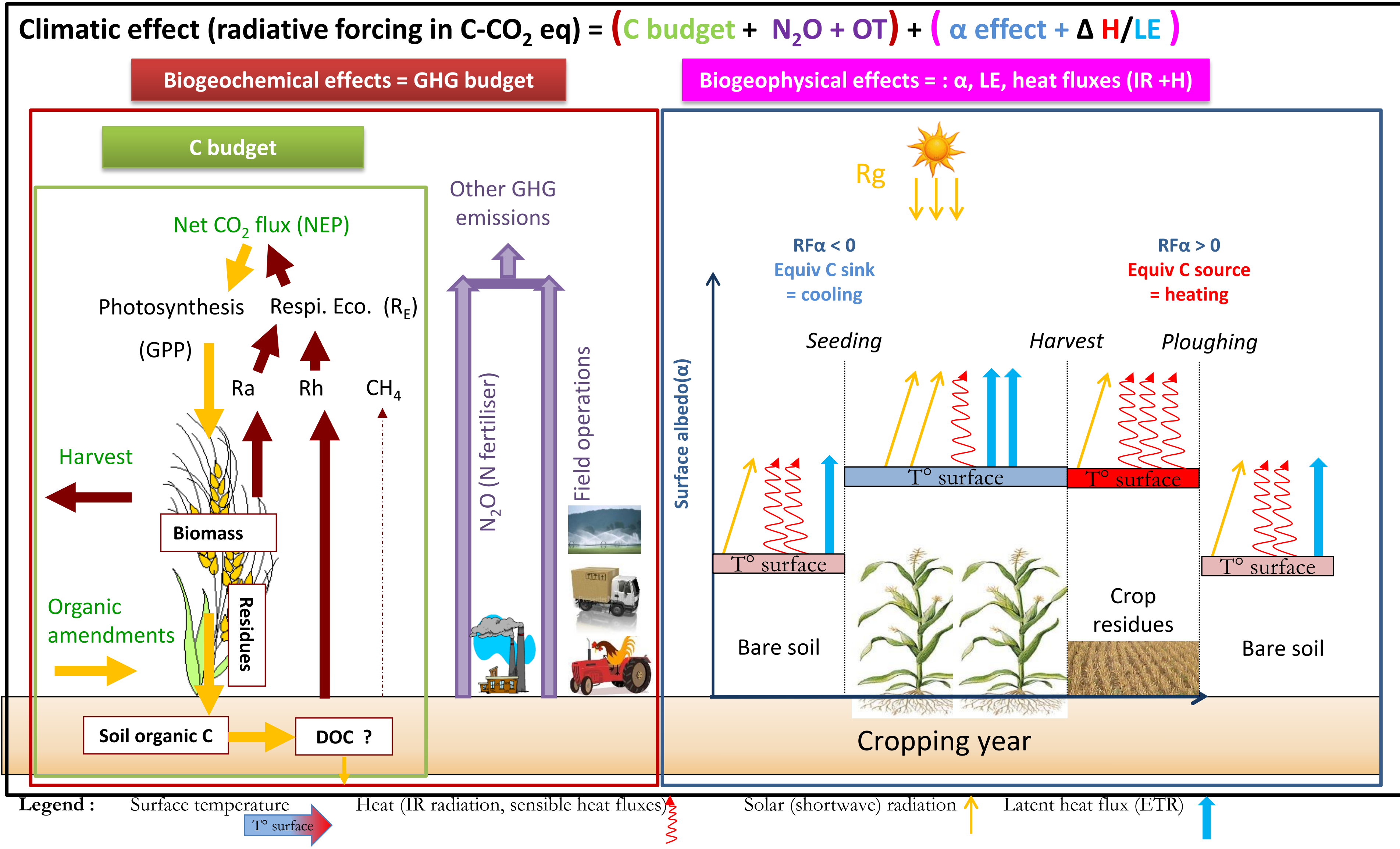
What about the biogeophisical contribution of cropland to climate ?

Which processes are involved ?

How to account for them ?

Effect of crops on climate

If biogeochemical effects have been widely studied, biogeophysical effects have been adressed only recently



First studies on albedo and biogeophysical effects on climate

- Among the first studies on Solar Radiation Management (i.e. modifying albedo to generate a cooling effect):
  - At the surface: e.g. Akbari (2009; 2012) estimated that painting all urban areas in white (increase in α) would lead to a 1°C cooling at mid latitudes,
  - On atmosphere: studies on atmospheric albedo ➔ e.g.. aerosol sulfate dispersion studied by Robock et al 2009 ➔ could have unintended and possibly harmful consequences on biosphere + risk of strong and imediate climatic effect if stopped

  ➔IPCC recommends progressive & reversible combined SRM and CDR (Carbon Dioxide Removal) approaches (e.g. on land surface

- Luyssaert et al. (2014) show that Land Management Change have as much impact on climate than Land Cover Change
- Studies on afforestation & deforestation: e.g. Bonan et al. (2004) show the reduction in sensible heat flux & increase in latent heat flux (evapotranspiration) with afforestation in tropical forest, theory of the Biotic pump, importance in accounting for biogeophysical effects of forest on climate ➔ Report of World Research Institute: https://www.wri.org/research/not-just-carbon-capturing-benefits-forests-climate
- First studies comparing biogeochemical and biogeophysical effects were on forest ecosystems (e.g. *Betts et al. 2000 ; Rottenberg & Yakir 2010 ; O'Halloran et al. 2011*) ➔ afforestation in toundra & mediteranean regions would cause such a drop in surface α that it would take 120-200 yrs of biomass productrion (CO_2 capture) to compensate for this effect,

First studies on albedo and climate mitigation

- For cropland, during many decades, studies were either focussing on :
  - Soil C storage and reduction of Green House Gases (GHG) emissions for climate mitigation,
  - Causes of albedo dynamics (Cresswell et al., 1993 ; Horton et al. 1996; Cierniewski et al., 2018…)
  - The effects of changes in management practices on biogeophysical effects (e.g. Muñoz et al. 2020; *Genesio et al., 2012; Davin et al. 2014; Luyssaert et al., 2014*),
  - The effect of Leaf Albedo Bio-geoengineering (Ridgwell et al. 2009; Sakowska et al., 2018).

Chlorophyl deficient soja ➔ high α

Normal soja ➔ low α

First studies on albedo and climate mitigation

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  - The effects of changes in management practices on biogeophysical effects (e.g. Muῆoz et al. 2020; *Genesio et al., 2012; Davin et al. 2014; Luyssaert et al., 2014*),

  - The effect of Leaf Albedo Bio-geoengineering (Ridgwell et al. 2009; Sakowska et al., 2018).

- But to compare biogeochemical effects with the RF_{α} caused by cropland management changes, the latter had to be converted in CO_2-eq ➔ stabilised methodologies to do so were missing,
- In recent years, though, methodological advances allowing to convert albedo effects in CO_2-eq raised awareness of the potential significative effects of RF_{α} on climate mitigation (see *Bright et al. 2015*).
- As a consequence, recent studies showed that for some management changes RF_{α} had impacts of the same order of magnitude than biogeochemical effects (Ferlicoq & Ceschia 2015; Carrer et al. 2018, Kaye & Quemada 2018; Lugato et al. 2020…).

Why albedo effects have been overlooked up to now ?

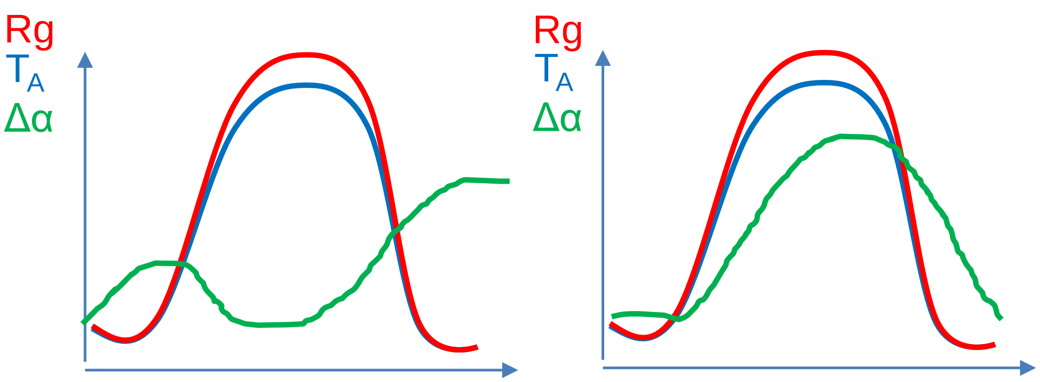
Most IPCC studies were calculating mean annual albedo induced radiative forcing (RFα) based on mean annual values of Solar global radiation (Rg), Transmittance (T_A) and changes in albedo of the land cover (Δα)

$$RF\alpha\ (W.m^{-2}) = -\,Rg \times T_A \times \Delta\alpha$$

$$T_A = \frac{Rg}{R_{TOA}}$$

$$\alpha_{\text{new system}} - \alpha_{\text{old system}}$$

However …



Mean annual RF calculated based on mean annual values of the 3 variables will be very different from mean annual RF calculated based on the yearly average of daily RF (calculated with daily values of the 3 variables) (Sieber et al. 2029) ➔ up to 96% underestimation of RF for cropland (Ferlicoq 2015)

Same mean annual values but very different daily/annual RFα

Never calculate RFα by using mean annual values of albedo, Rg and atmospheric transmittance (T_A) !!!

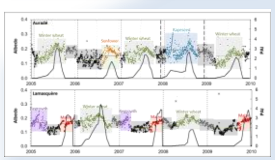
Various spatial and temporal scales of study

At the Regional Space Observatory

Gaillac (81)

Biogeophysical effects of cropping sytems

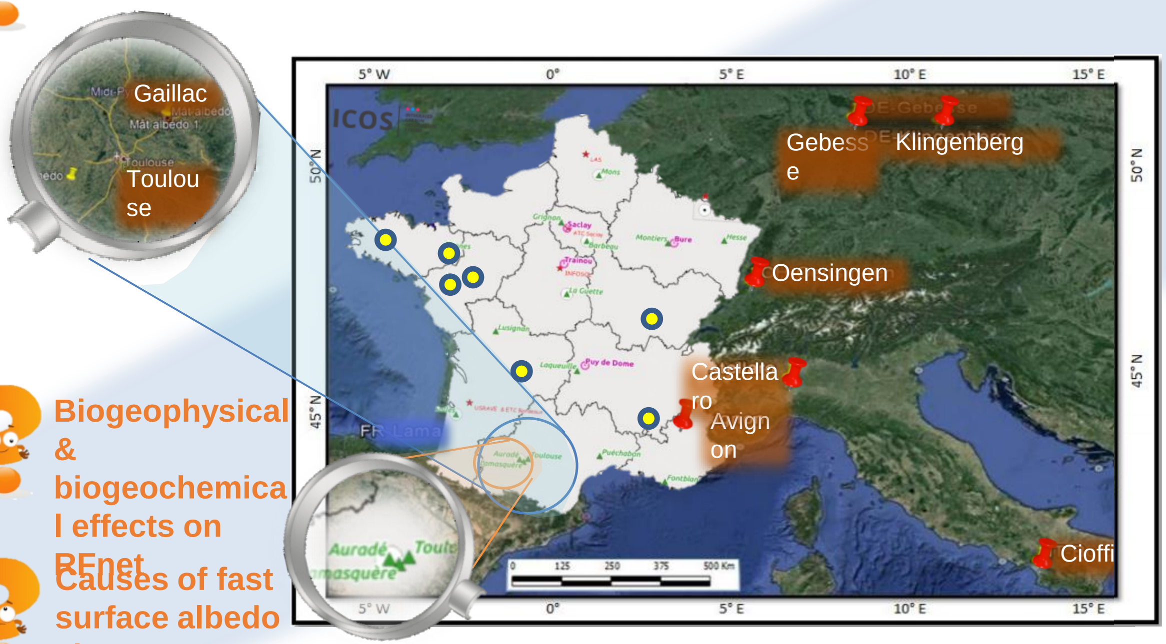
Lamasquère (31)



Biogeophysical & biogeochemical effects on RFnet

Causes of fast surface albedo changes

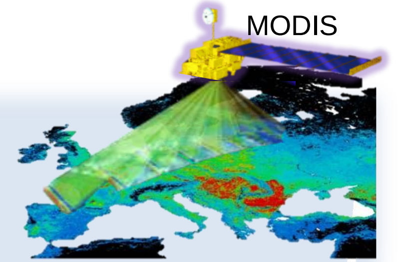
In situ measurements/Southwest France



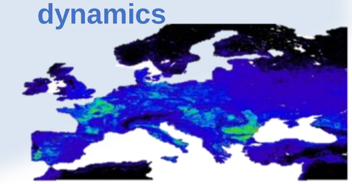
French grassland sites

European cropland ICOS sites

MODIS



Surface albedo dynamics



RFα

Consequences of cropland management changes on biogeochemical & biogeophysicial (mainly RFα) components of RFnet

Satelite data and /or modelling at European scale

What do local scale studies teach us ?

Methodology for in situ albedo and RFα measurements

Dynamics of surface albedo :

① **Daily weighted average albedo (α)**
Half-hourly measured albedo (net radiometer) and weighted by incident solar radiation

② **Radiative forcing equation. We choose a bare soil albedo (measured on each site) as a reference for croplands & grasslands (arbitrary reference).**

$$RF\alpha\ (W.m^{-2}) = -\ SWin \times T_A \times \Delta albedo$$

T_A is atmospheric transmittance $T_A = \frac{SW_{IN}}{R_{TOA}}$

$\alpha_{daily} - \alpha_{reference\ system}$

③ **Annual radiative forcing was calculated over a cropping year by using the dynamics of each terms of the previous equation.**

if α increase, $FR_\alpha < 0$ (cooling effect, Eq. C sink)
if α decrease, $FR_\alpha > 0$ (warming effect, Eq. C source)

④ **Conversion in CO_2-eq based on AF method (*Betts et al. 2000*)**

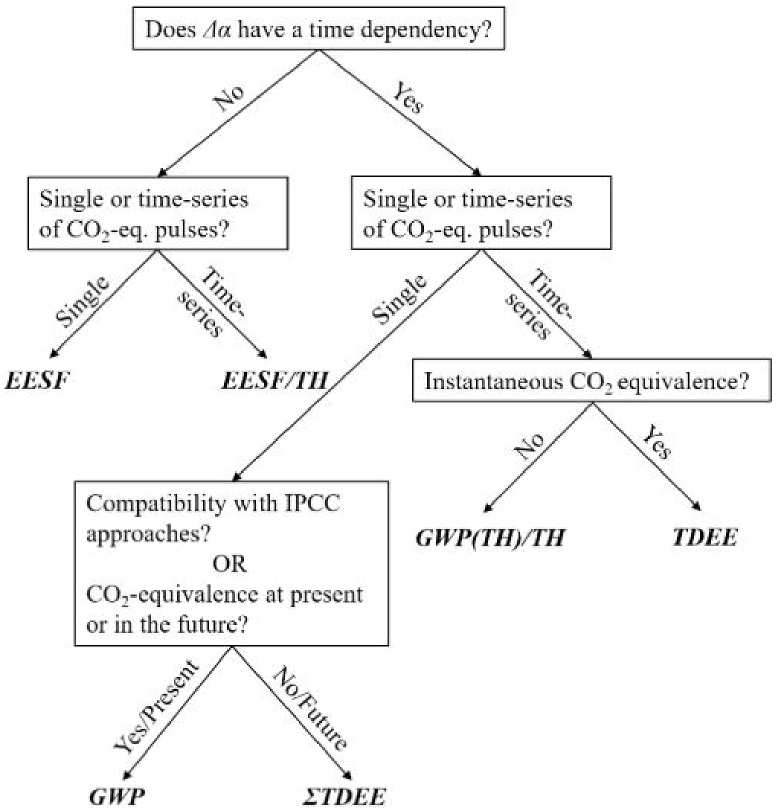
$$RF_{\alpha y}(in\ Kg\ CO_2 - eq) = \frac{A\ RF_{\alpha y}(W \cdot m^{-2})\ \ln 2\ pCO_{2,\mathrm{ref}}\ M_{\mathrm{CO_2}} m_{\mathrm{air}}}{A_{\mathrm{Earth}}\ \Delta F_{2\mathrm{X}}\ M_{\mathrm{air}}\ AF}$$

45

AF depends on the time horizon considered

Other methods for converting RFα in CO_2-eq

<u>More complex methods based on Bright & Lund (2021):</u> To choose the more appropriate method, analyse this figure



TDEE for « Time-Dependent Emissions Equivalent »
This method avoids a possible overestimation of the CO_2 equivalents encountered in methods that do not take into account the temporal albedo variation. For its application, it requires not only a pulsed CO_2 emission time series (difficult to obtain), but also the user's definition of a priori scenario of inter-annual temporal variation of surface albedo.

GWP pour « Global Warming Potential»
Widely used to compare the climatic effect of surface albedo radiative forcing with that of other GHG emissions, GWP, is also a time-dependent conversion method. It represents the accumulation of radiative forcing (RF$\Delta\alpha$) following a pulsed emission of CO2 over a time horizon (TH). The user will have to define a priori scenario of inter-annual temporal dependence of the albedo variation.

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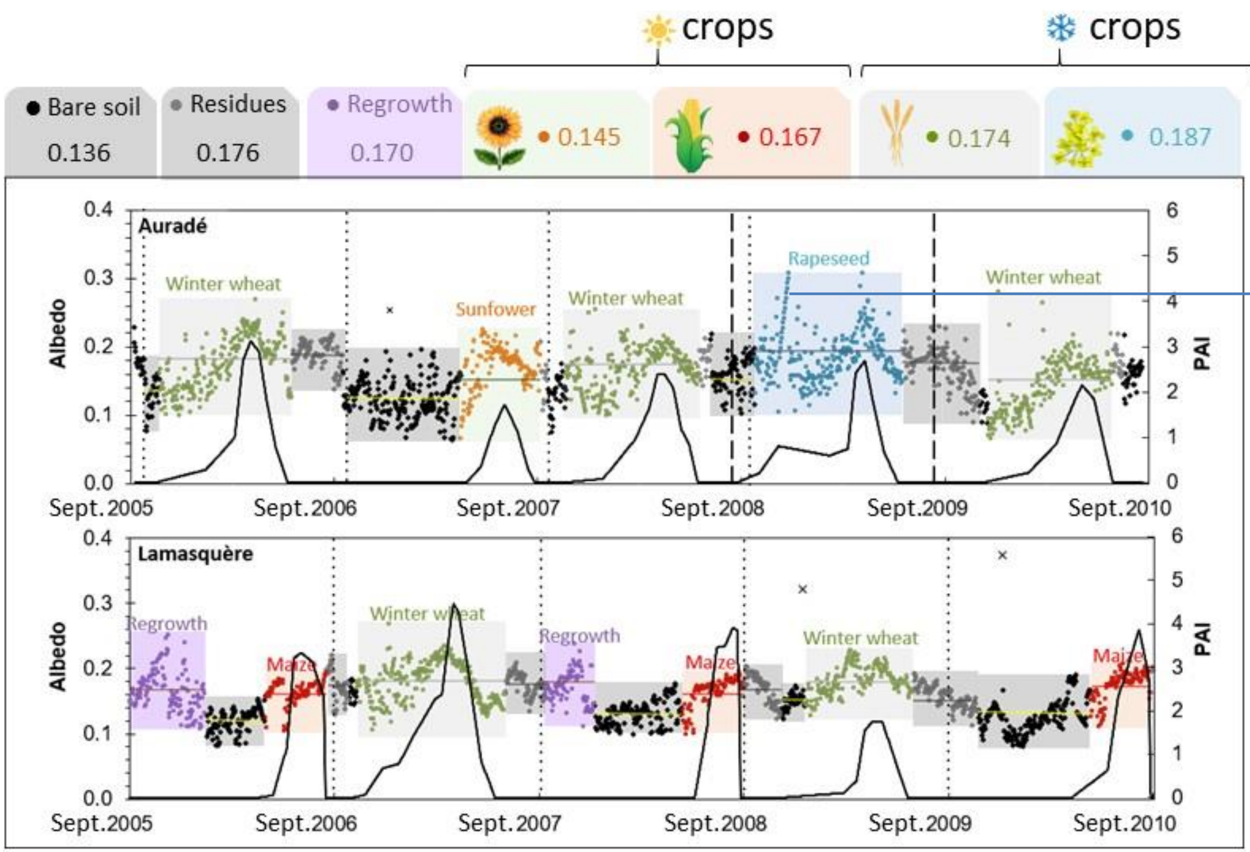
How do cropland status affects surface albedo ?



The rapeseed suffered from November **drought and frost** that increased surface albedo because of leaf damage + snow.

Land Cover :

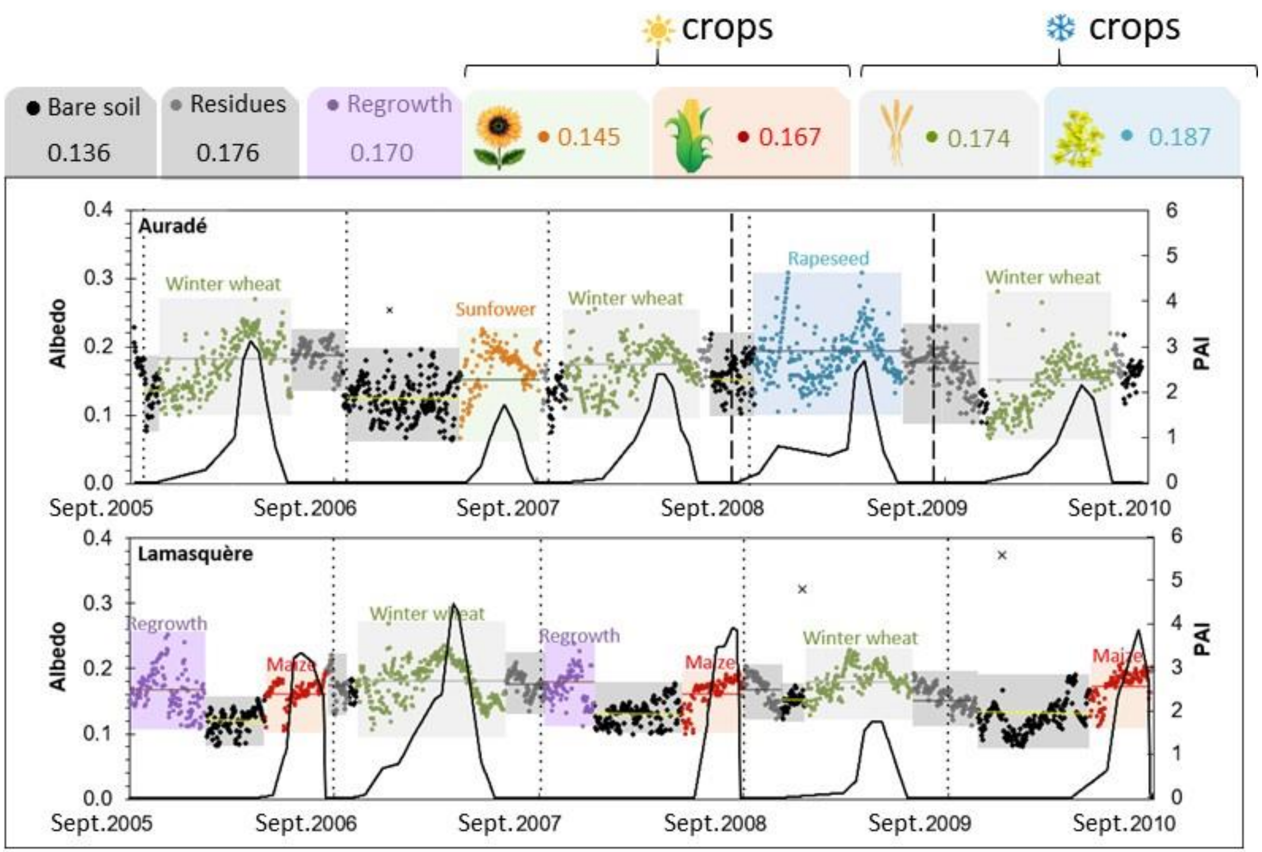
$\alpha_{residues} \approx \alpha_{crop} \approx \alpha_{S.regrowth} > \alpha_{bare\ soil}$

Crop type:

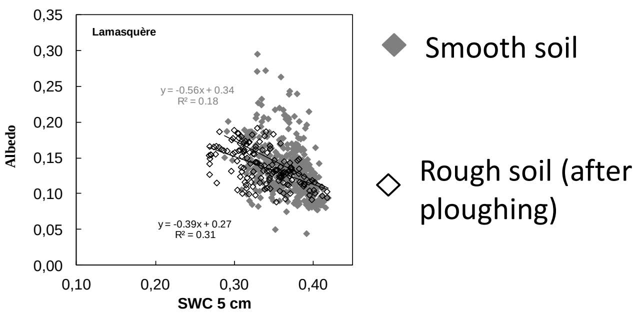
$\alpha_{rapeseed} > \alpha_{WW} > \alpha_{maize} > \alpha_{sunflower}$

In order to increase albedo at croplands, avoid bare soil periods ➔ adapt crop rotations, cover the soil with crop residues or cover crops during fallow

How do cropland status affects surface albedo ?



Rain decreases the albedo of the soil as water darkens the soil



Ploughing may also decrease surface albedo (wet soil at the surface, less crop residues at the surface)

In general, surface albedo increases with the green plant area index (PAI) but the response is crop dependant;

- For winter wheat and rapeseed, α reaches its maximum at PAI_{max},
- For maize & sunflower, the α response to PAI is less pronounced,
- For sunflower maximum albedo occurred before PAI_{max}.

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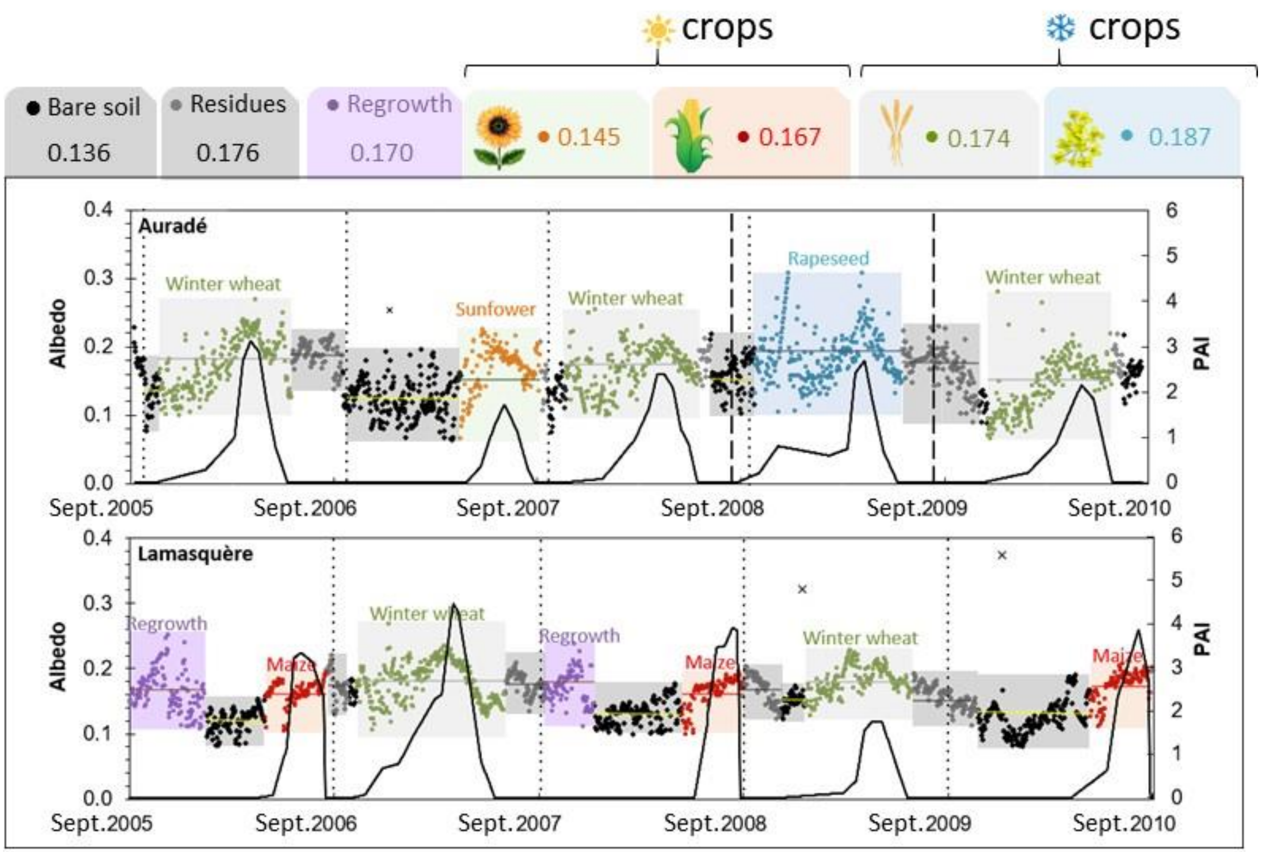

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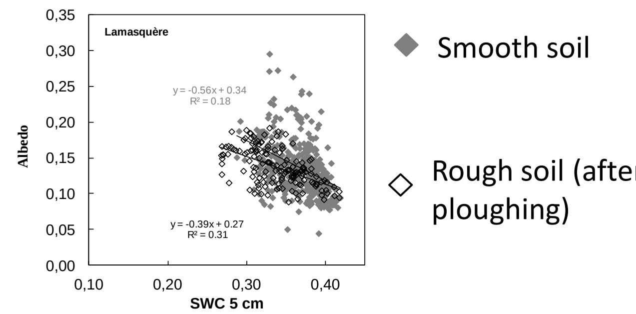

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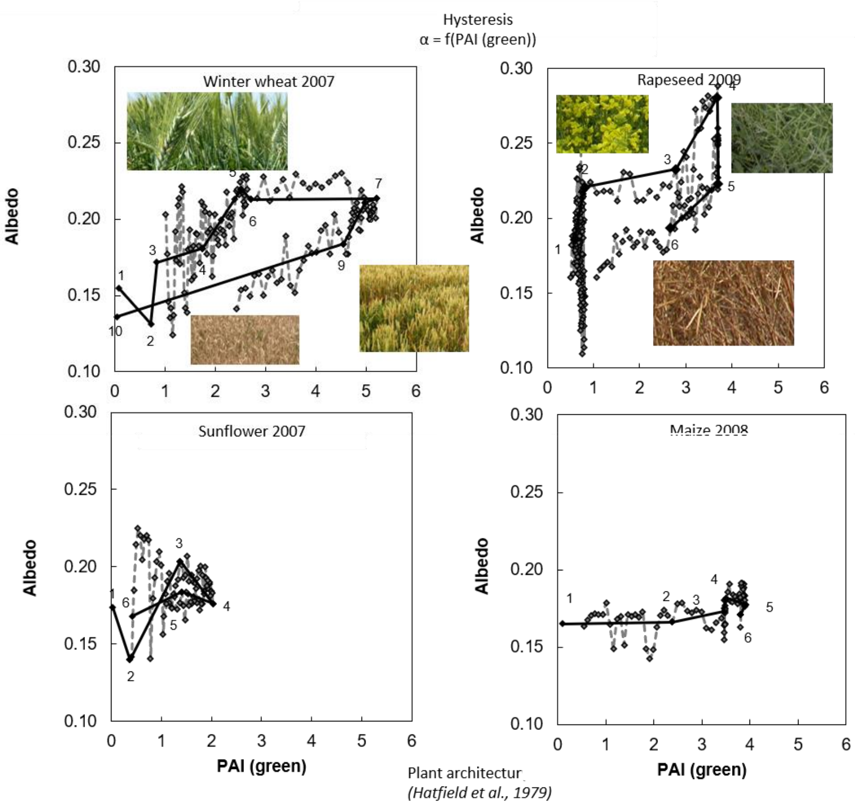
How do crop development affects surface albedo ?

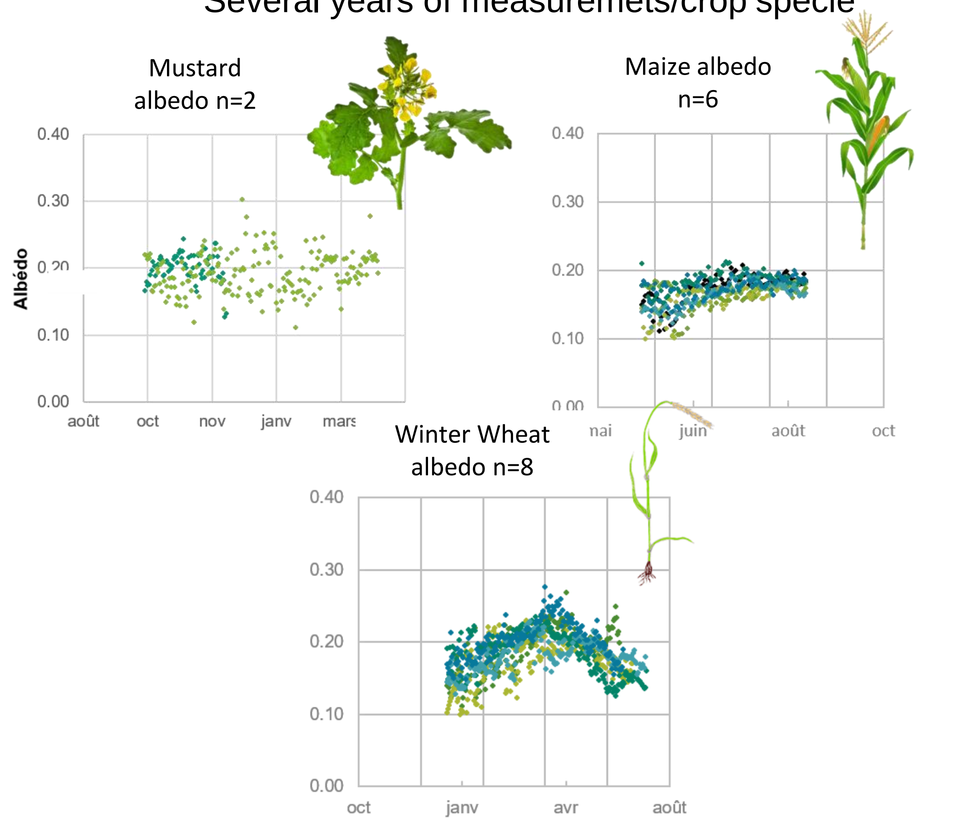
Crop phenology effect on surface albedo



For a same green PAI as during the growing phase, during senescence albedo is lower because yellow tissues also trap light

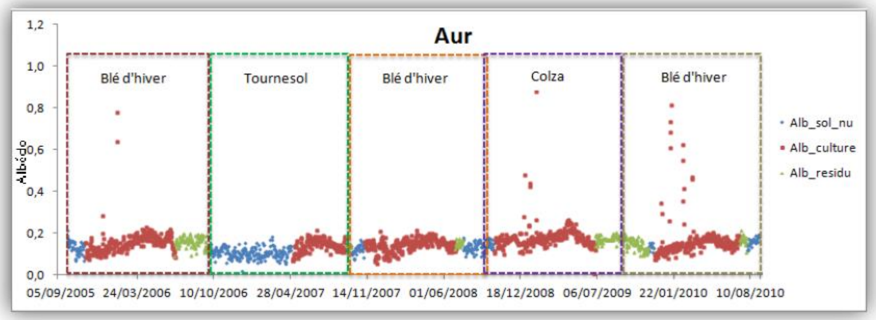
Albedo dynamics differ accroding to crop species

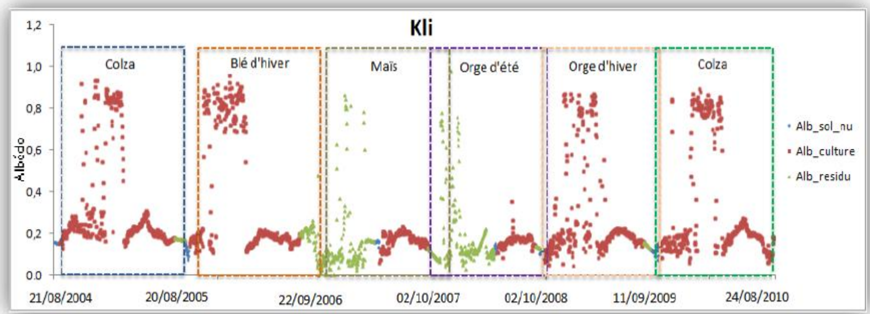
Several years of measuremets/crop specie

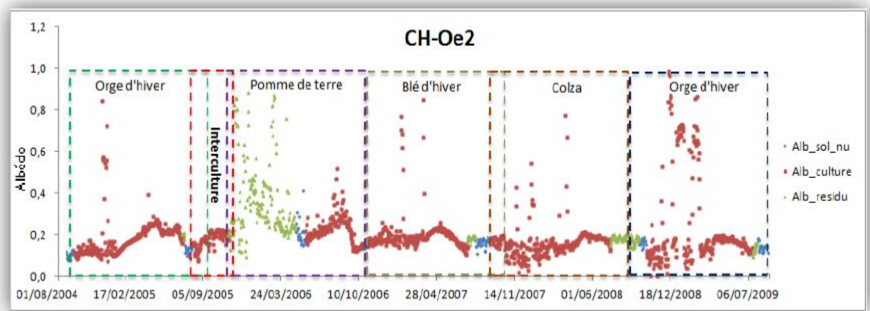


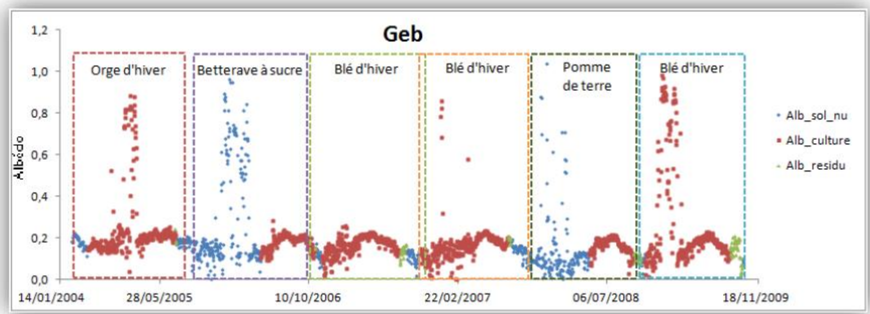
European multi-site analysis of surface albedo dynamics

ICOS sites









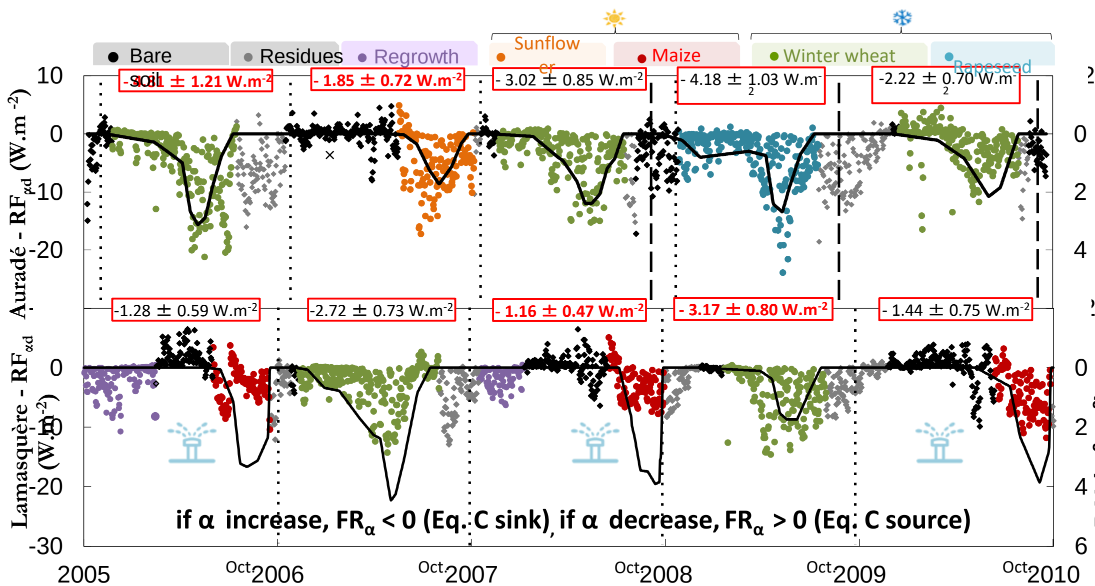
Values > 0,4 correspond to snow periods

Similar conclusions as for the previous slides concerning Auradé and Lamasquère

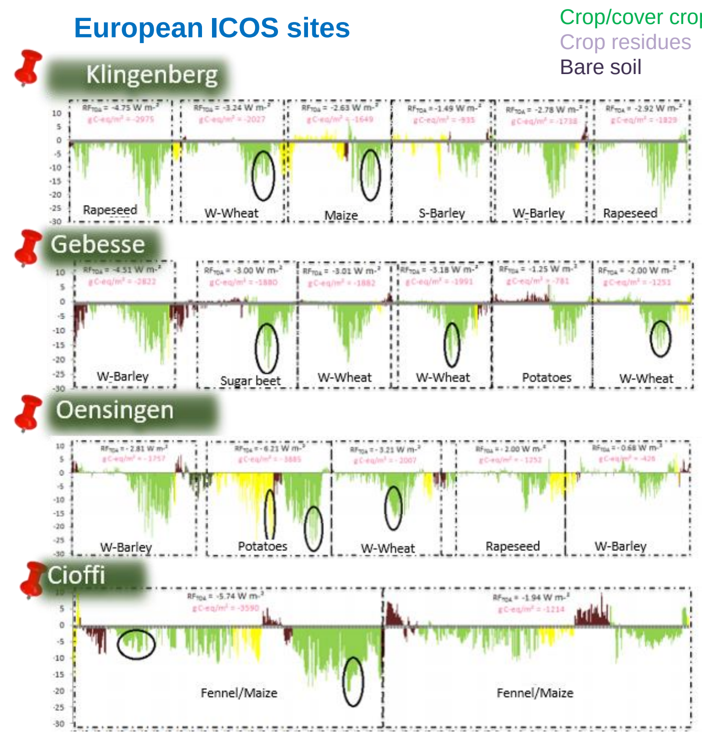
RFα induced by cropland albedo dynamic in reference to bare soil

Illustrates the combined effect of albedo dynamics with those of Rg and TA

In situ measurements/Southwest France



European ICOS sites



Take home message:

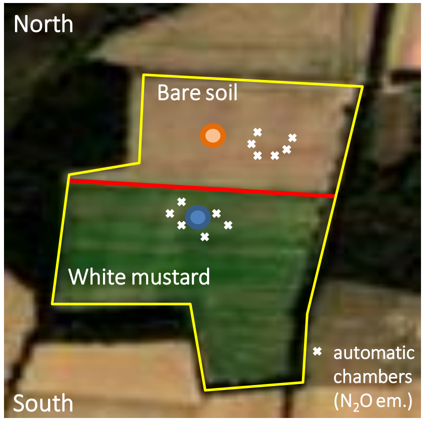
- Soil coverage may contribute to a “cooling” albedo effect,
- Same observations at all European flux sites
- **But !!! arbitrary reference albedo**

As cover crops seem to be a good lever to store C in the soil and increase surface albedo we analysed their combined biogeochemical and biogeochemical effects on climate in comparison with having bare soils during the fallow period

Comparative in situ analysis of all RFnet components – bare soil vs cover crop

A white mustard cover crop was grown during 2,5 month between october and December 2013 on half of the plot. The other part was left in bare soil during the whole fallow period

ICOS Lamasquère site



<u>Measured variables :</u>

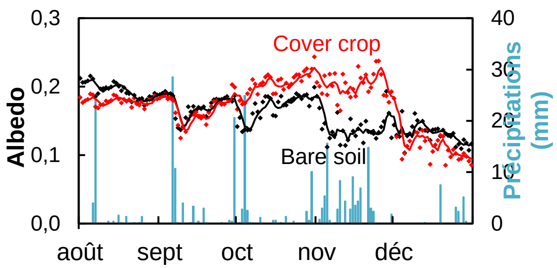
- CO_2, N_2O, water & energy fluxes
- Soil temperature & humidity at 0-5 cm
- Soil heat fluxes
- Solar incident/reflected radiation (short & longwave)

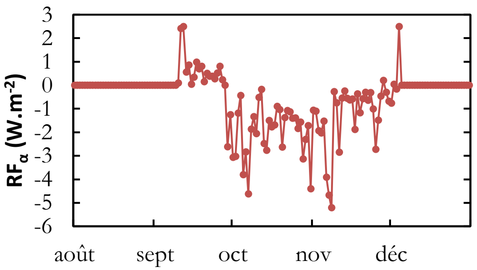
<u>Objectives :</u>

- Difference in surface albedo and RF induced by cover crop (CC)
- Effect of CC on :
  - Surface IR radiations & soil temperature
  - Sensible heat fluxes (hot eddys at the surface)
  - Latent heat fluxes (evapotranspiration)
  - C and GHG budgets

Comparative in situ analysis – radiative effects of cover crops

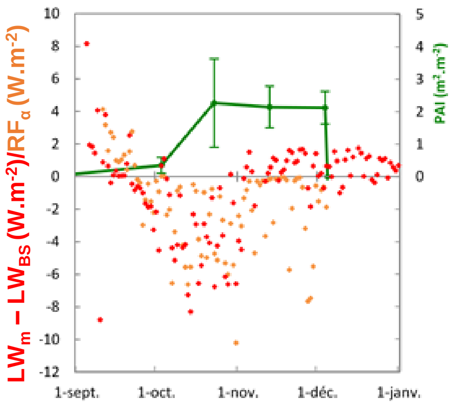
1. Shortwave (albedo) effect (RFα)





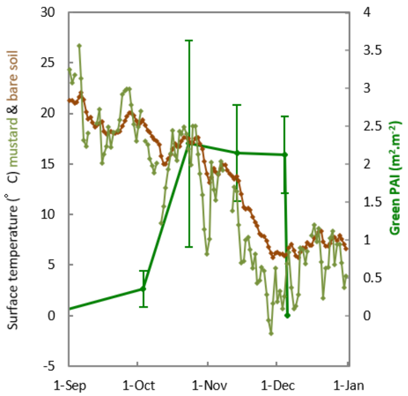
➔ Δα causes a cooling effect

2. Longwave effects



➔ Longwave effect ≈ RFα in term of intensity (not necessarily in term of cooling effect)

3. Soil temperature

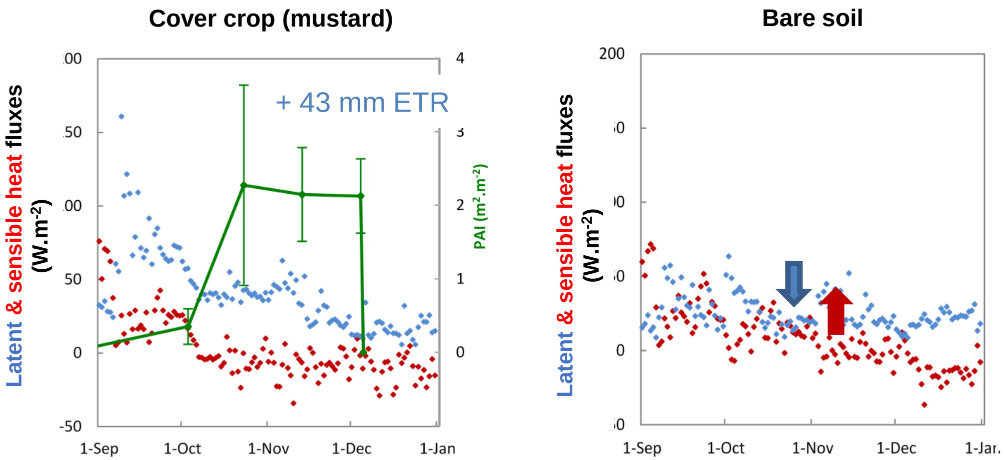


➔ Mean difference of 2.5°C

➔ Likely **slowdown** in organic matter mineralisation (and consequences on soil CO_2/N_2O fluxes)

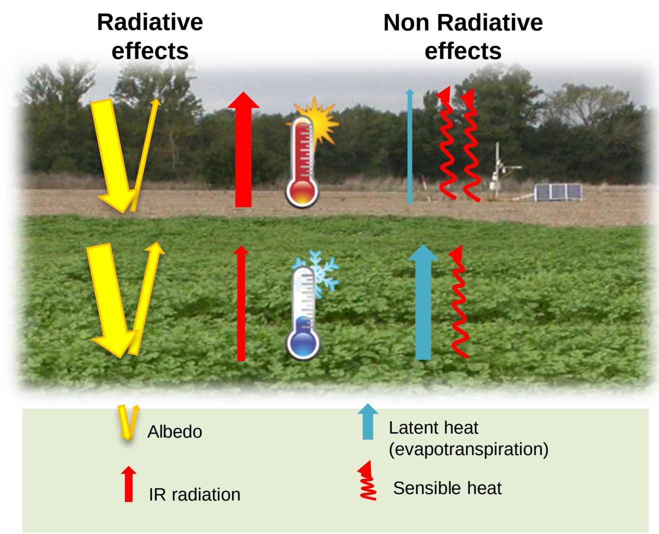
Comparative in situ analysis – non radiative effects of cover crops

Effects on latent and sensible heat fluxes



- ↑ evapotranspiration & ↓ sensible heat fluxes causes local surface climate cooling (*Boucher et al., 2004*) ➔ Natural air conditioner !! ;-)
- But this effect is difficult to express in term of radiative forcing (*Pielke et al., 2002), especially at local scale*

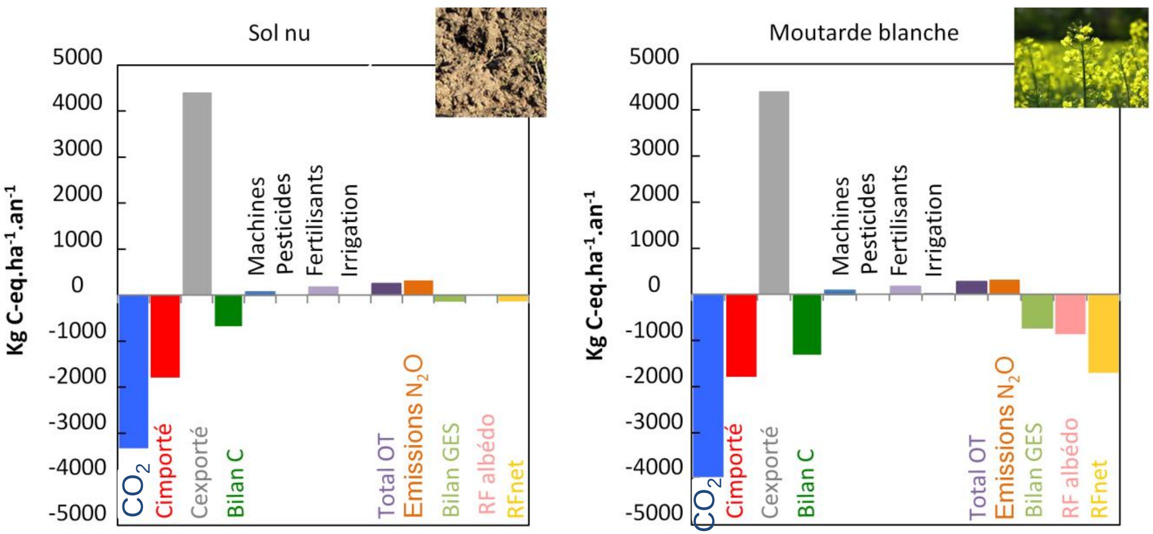
Summarizing cover crop biogeophysical effects



Global effect on climate of CC is difficult to estimate (requires coupled surface-atmosphere modelling exercises) but local/regional effect on perceived temperature at the surface could be significant (*Georgescu et al., 2011*).

Effect of cover crops on the components of the GHG Budget + RFα

Ceschia et al. (2017)



Ferlicoq (2016), Ceschia et al. (2017)

- The **differences in C & GHG budgets** were mainly **caused by the C storage effect** (but short term effect ➔ very depleted soil in OM) in spite of a low CC biomass production (2.2 t DM/ha) compared to mean regional figures (4 t DM/ha),

- Increase in N_20 emissions and GHG emissions from field operations were negligible,

-Albedo RF in CO_2-eq was calculated considering that CC would be maintained over the next 100 yrs

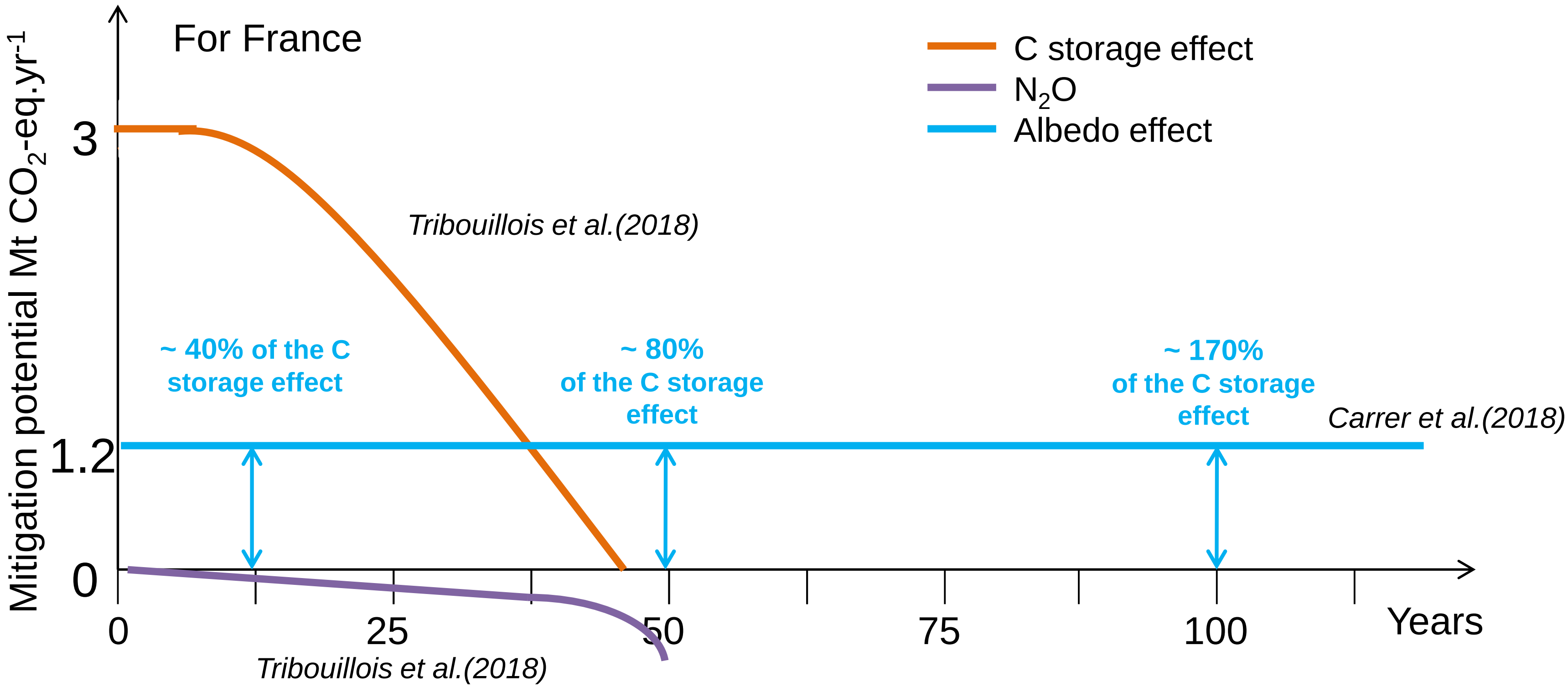
-Rather **low RFα because CC was grown in late fall** with low TA and Rg (and destroyed in early December) ➔ **this effect would have been close to 10 times larger if cover crop had been grown till spring** (common in our area ; see Ferlicoq & Ceschia, 2015),

But is it appropriate to compare RFα in CO_2-eq with the C/GHG budget components? ➔ albedo effects are local while GHG effects are global, C storage potential is limited…

Whats is the true climatic effect of cover crops if implemented at large scale?

Unfortunately, non of the current Earth system models used by the IPCC are able to simulate most crop management changes (including cover crops) ➔ are the IPCCs recommendations for climate mitigation the most efficient ones ?

Comparison of cover crop C and α effects on the long term vs short terms



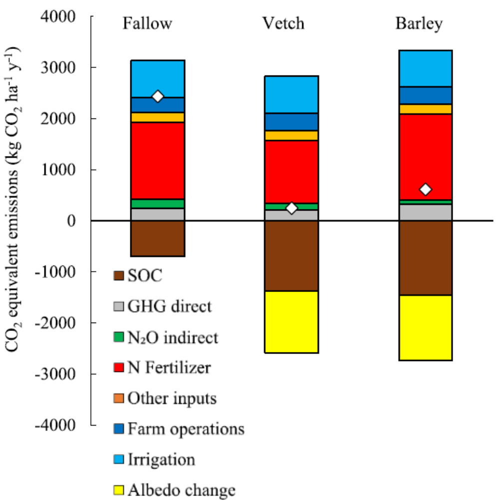
In the short term the albedo effect is lower than the storage effect of C intermediate crops but integrated over 100 years it is the reverse

Climate change mitigation of cover crops (vs bare soil) in time

Several other studies tend to show that :

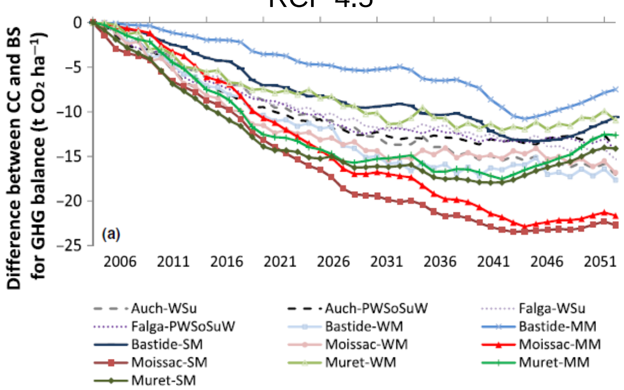
- the carbon storage effect of the cover crops could be limited in time : new equilibrium reached after 45-50 year,
- N_2O emissions may decrease on the short term but then increase 15-50 years after cover crop introduction ➔ Adapt N fertilisation after cover crop destruction ➔ integrated soil fertility management (Guardia et al. 2019 ; MERCI Meth.)

In-situ data in Spain (*Guardia et al. 2019*)

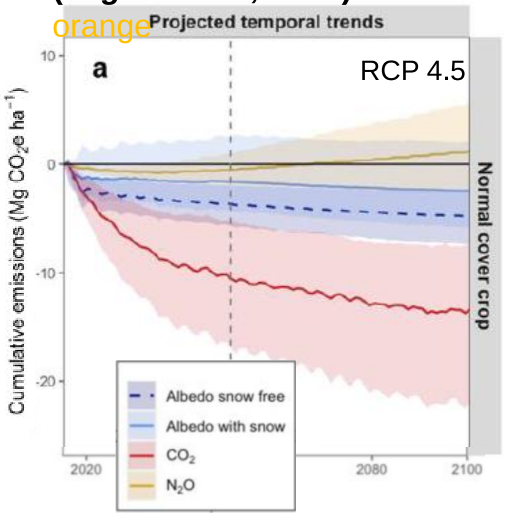


STICS simulations in France (*Tribouillois et al., 2018*)

RCP 4.5



DayCent simulations over Europe (*Lugato et al., 2020*) : red + orange



Also albedo effects of cover crops are in the same range as their C & GHG effects

Climate change mitigation of cover crops (vs bare soil) in time

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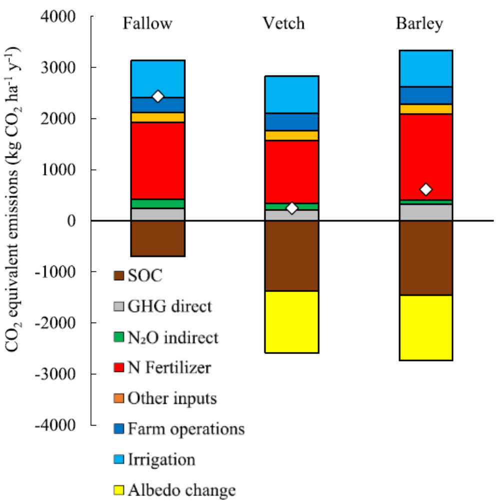

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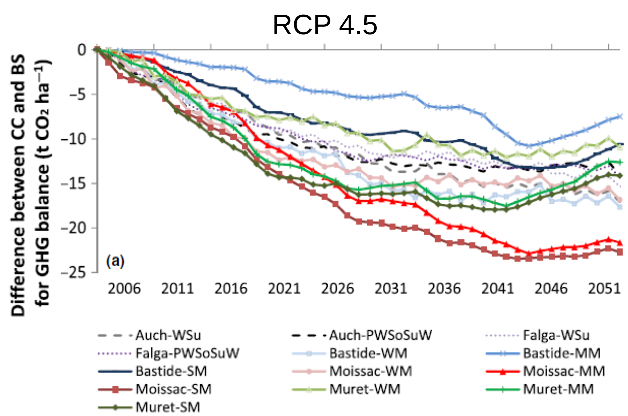

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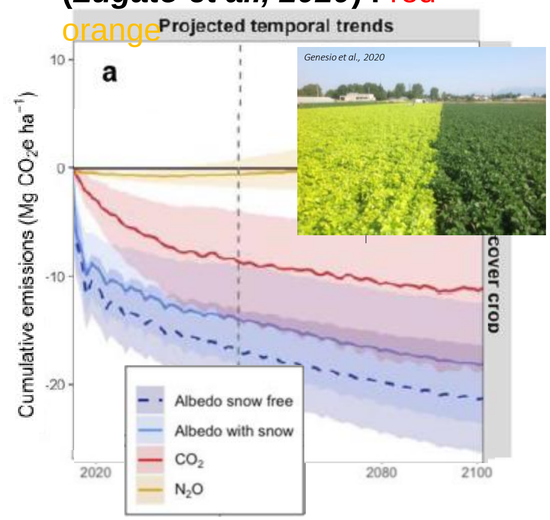
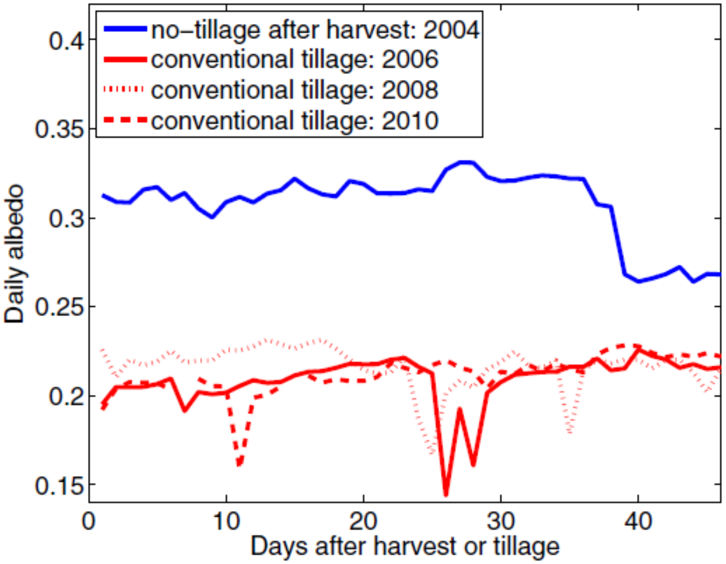
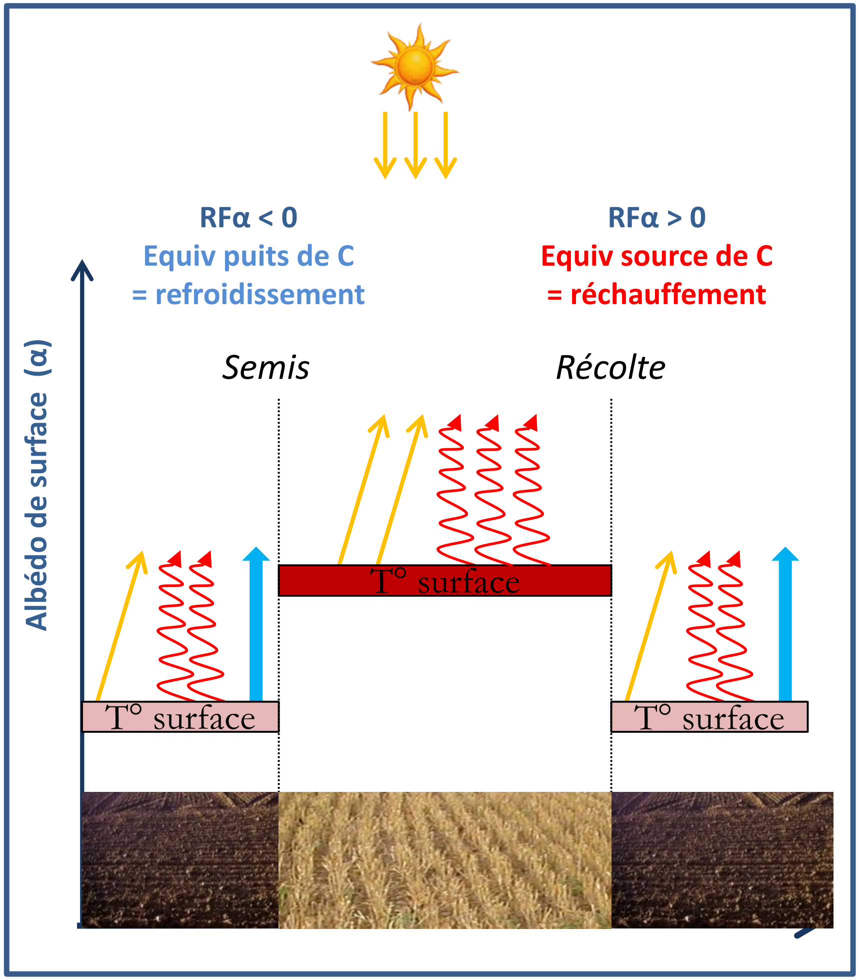


Also albedo effects of cover crops are in the same range as their C & GHG effects or even higher when cover crops species/varieties with a high albedo are choose (e.g. deficient chlorophyll mutants)

Effect of soil work on surface albedo and energy budget



Davin et al. 2014



This widespread practice in Europe would decrease the air temperature in summer by 2°C during heat peaks. (Davin et al. 2014).

Unfortunately the maintenance of residues (similar to mulching) greatly reduces the evaporation of the soil which increases the emissions of heat from the surface (Infra Red radiation). Part of the benefit of the increase in albedo (less energy available on the surface) is therefore lost as heat emissions increase (unlike CI).

No effect on soil organic C stocks according to recent studies (only redistribution effect of C in the soil)

General recommandations for climate mitigation

Therefore, from a climate warming mitigation point of view:

- Implement cover crops in suitable areas (soil + climate) to wiimprove the C, GHG, albedo, heat flow effects: it's the climate jackpot!!

- Promote regrowth: superficial tillage, when it is carried out in areas where it can promote spontaneous regrowth, is to be encouraged because allows to maintain a high albedo, to store C, to limit the heat fluxes (to be considered according to climatic zones? According to seasonal climate forecasts?),
- If too dry to promote spontaneous regrowth or to grow cover crops, keeping residues on the surface increases albedo, but the associated climate gain is largely lost through increased surface heat flows (soil temperature increases).

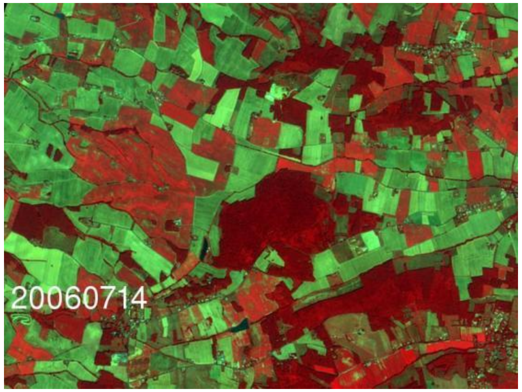
- Avoid ploughing in summer because it decreases albedo (+soil drying, erosion…). Better postpone it until the fall.

- Combinations of several practices are of course possible/to encourage (e.g. regrowth or maintenance of residues in summer and planting of cover crops in autumn).

Finally, farmers that have long been critiscised because of the impact of their activity on the environment, could be valuable allies in the fight against climate change !!!

Thanks for your attention !

Analysing carbon, GHGs and energy fluxes/budgets of agro-ecosystems for more efficient climate change mitigation strategies: approaches combining in situ data, modelling and remote sensing



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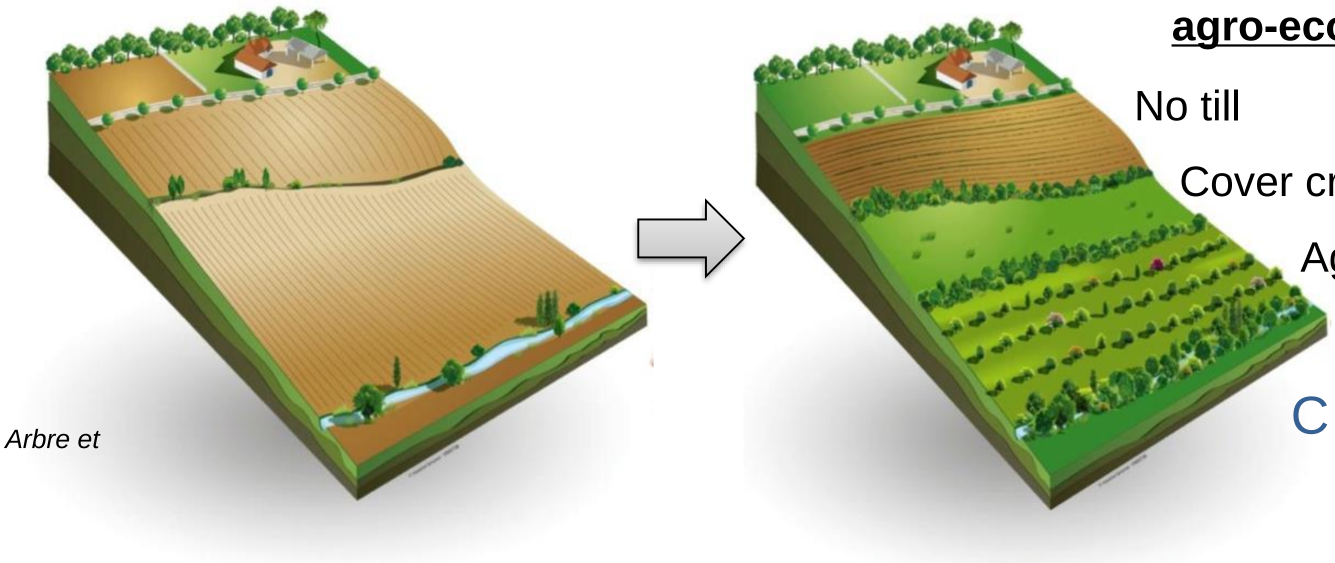
Part 2 : Earth observation and modelling

How will remote sensing and spatial modelling help us quantify the different components of carbon, water and energy fluxes at larger scales?

Societal issues and context

Because of climate change and other environmental issues, current challenging of conventional agriculture

⇨ Towards agro-ecological practices at the territorial/national levels



Illustrations: Arbre et Paysage 32

Lack of multi-criteria spatial diagnostic tools to assess the situation, guide these new practices and quantify their environmental benefits (ecosystem services) and possibly their disservices.

Strategic issues for the agricultural profession/policy makers

Agroecology: what are we talking about?

A gradient of ecological intensification of agrosystems:

- Improve input efficiency
  → *intra-plot modulation of fertilizer inputs (precision agriculture)*

- Substitution of chemical fertilizers
  Use of green fertilizers (leguminous cover crops) but need decision support tools based on new rules, from the plot to the farm (or territory)

- Re-design of crop systems based on strong species diversification
  → *New reasoning tools and methods, high importance of observation and defining decision rules in situations of incompleteness of knowledge*

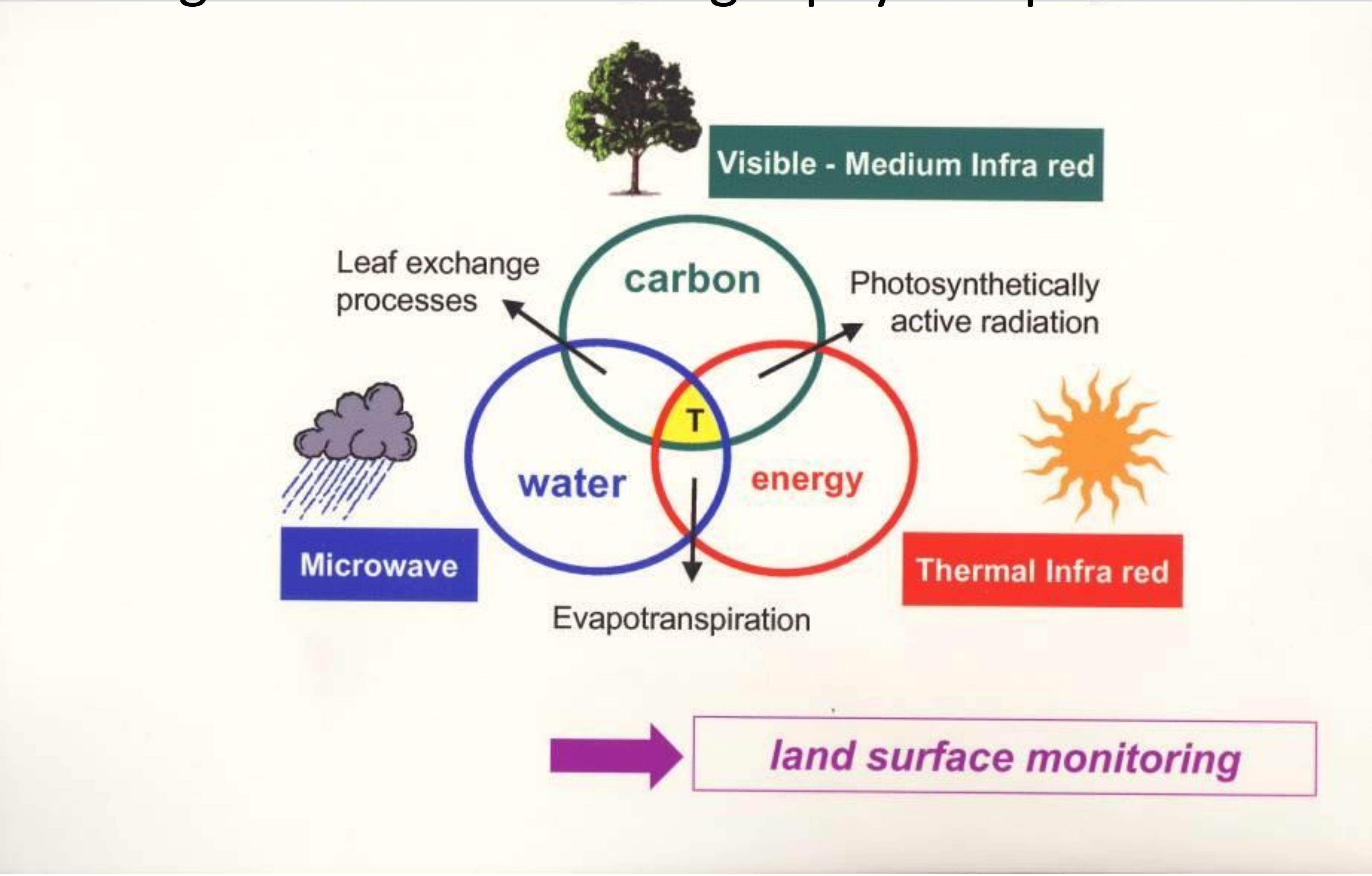
weak agroecology

+++ observations
+++ anticipation
+++ management with incomplete knowledge

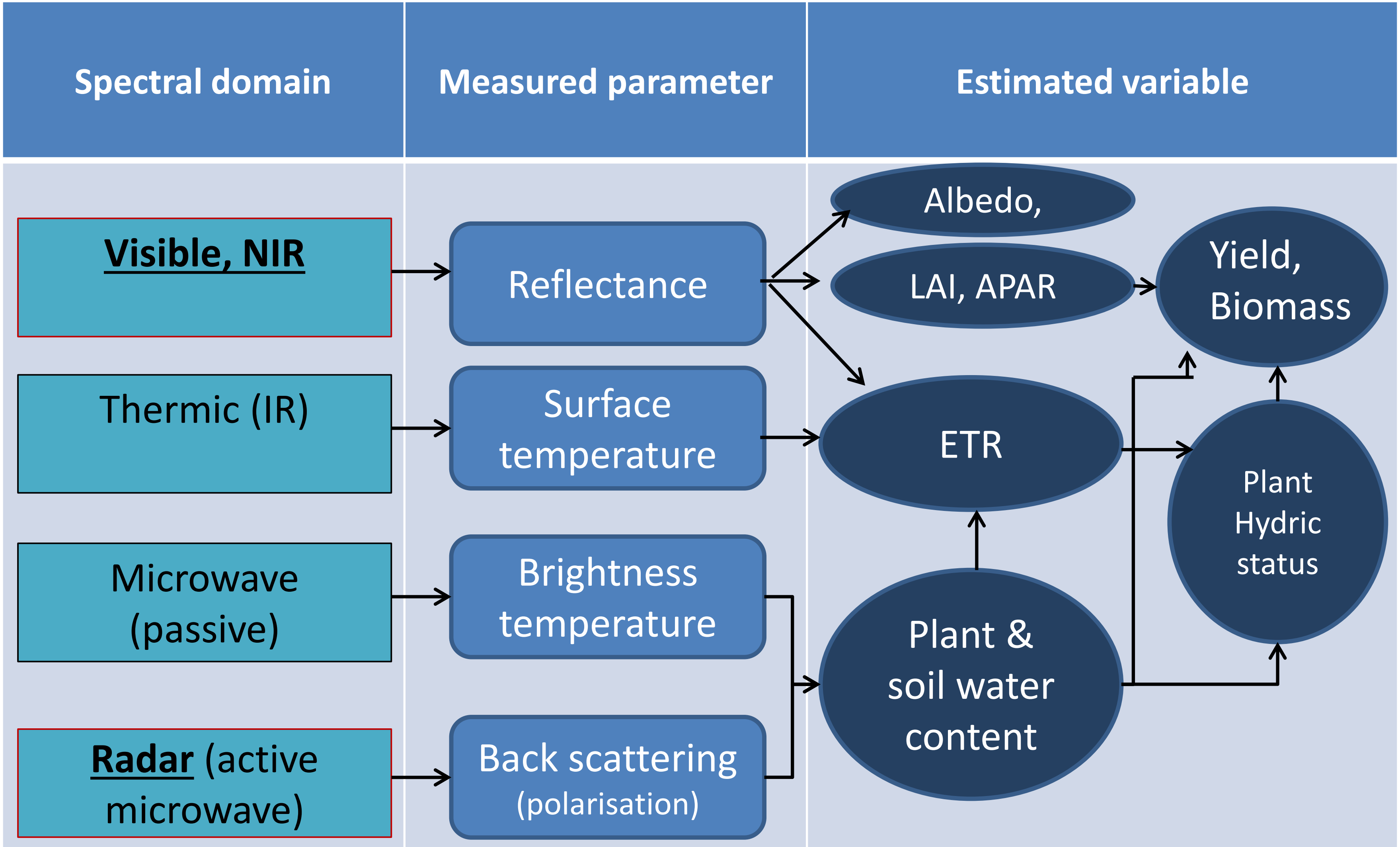
strong agroecology

Remote sensing combined with modelling can help the transition (mainly first step)

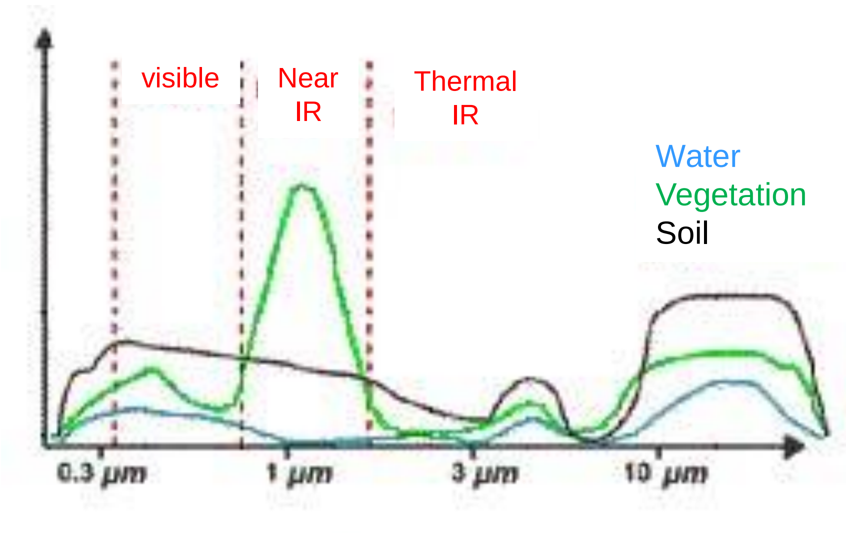
Spectral domains and their use for assessing biogeochemical and biogeophysical processes

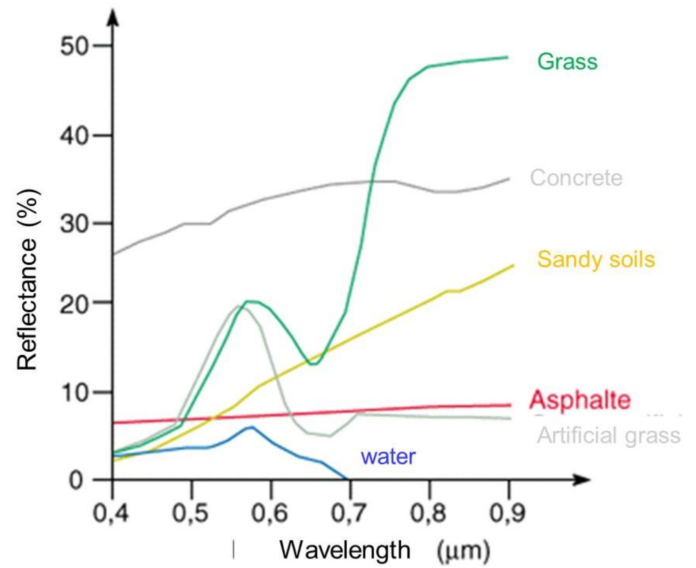


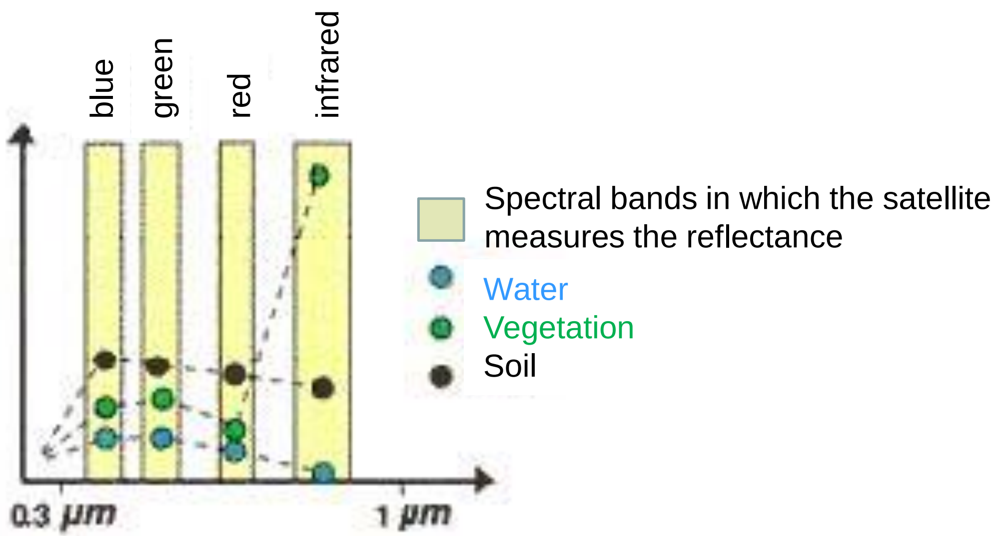
Spectral domains and their use for assessing biogeochemical and biogeophysical processes

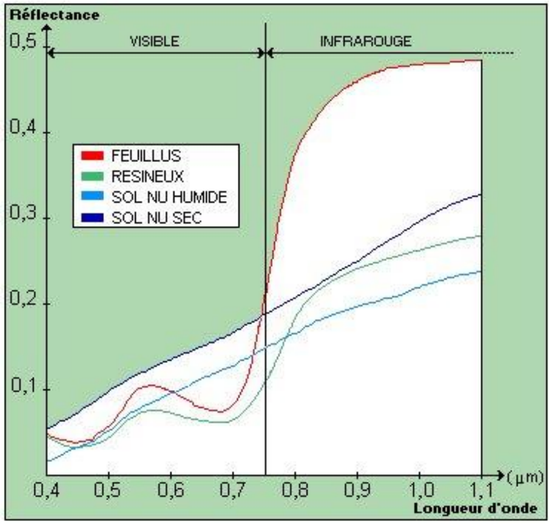


Spectral resolution (Optical domain)



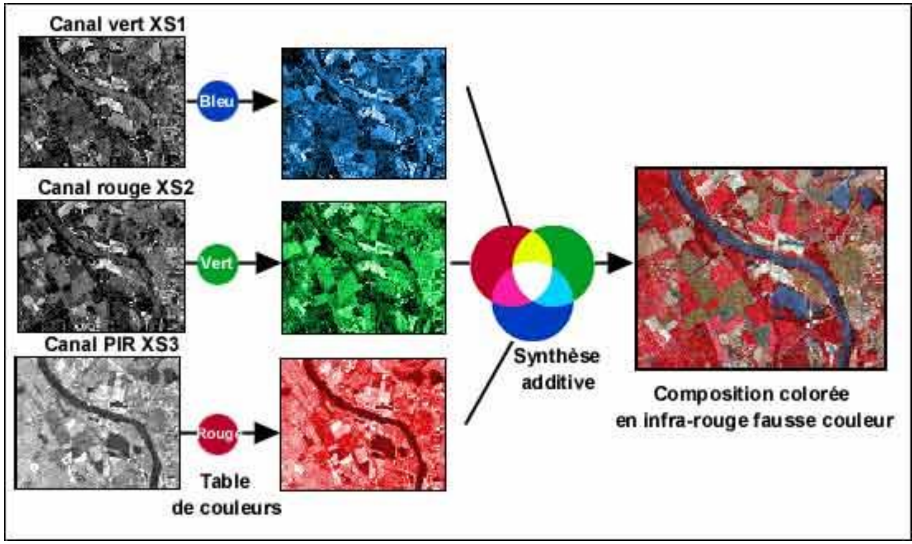




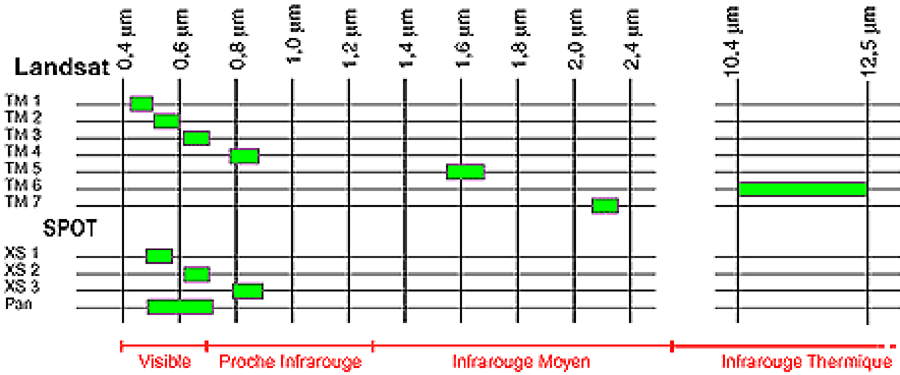


Multispectral or multiband RS

- For earth observation satelittes, data are recorded in tipically 3 to 8 narrow spectral bands simultenaously.



- The Thematic Mapper (T.M.) sensor on LANDSAT 5 has 7 bands between 0,45 et 12,5 mm (3 in the visible, 1 in the NIR, 2 in the MIR and 1 in the thermal infrared).

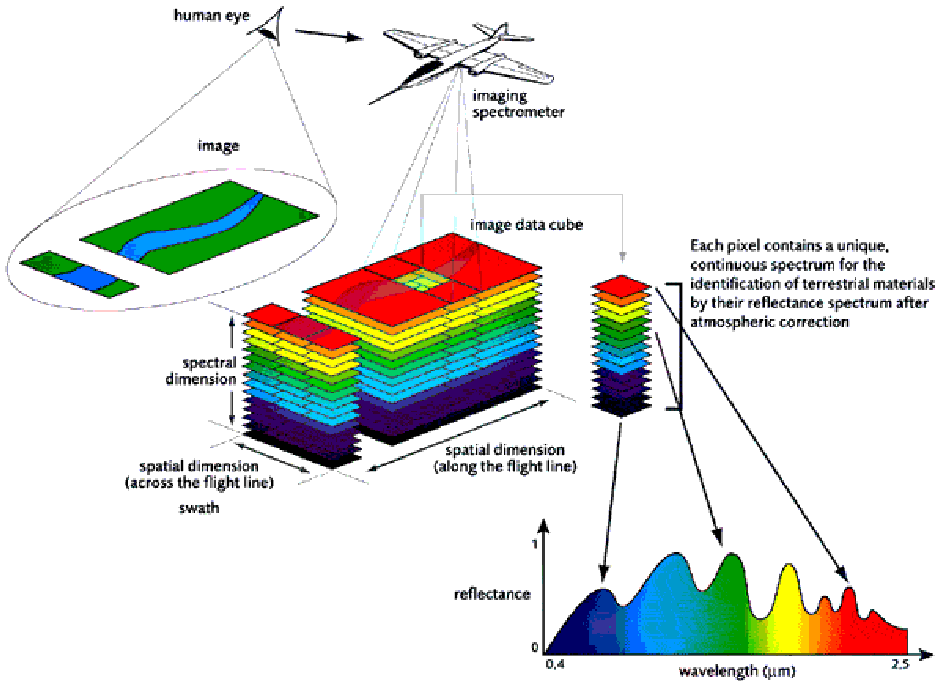


Hyperspectral data

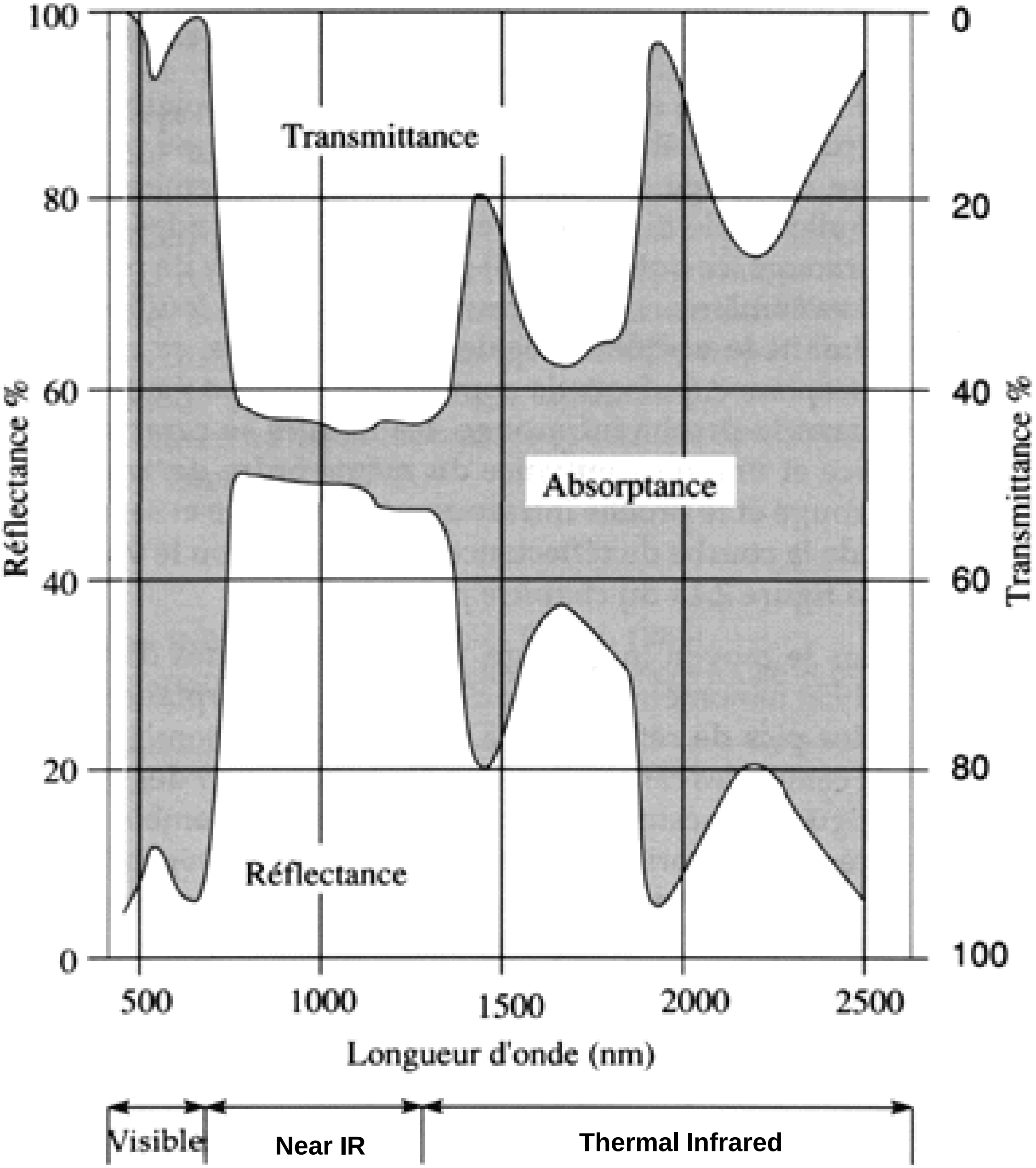
Often more than 200 narrow spectral bands (a few nm) and often contiguous in the visible, NIR, MIR.

Ex Hyperion satellite

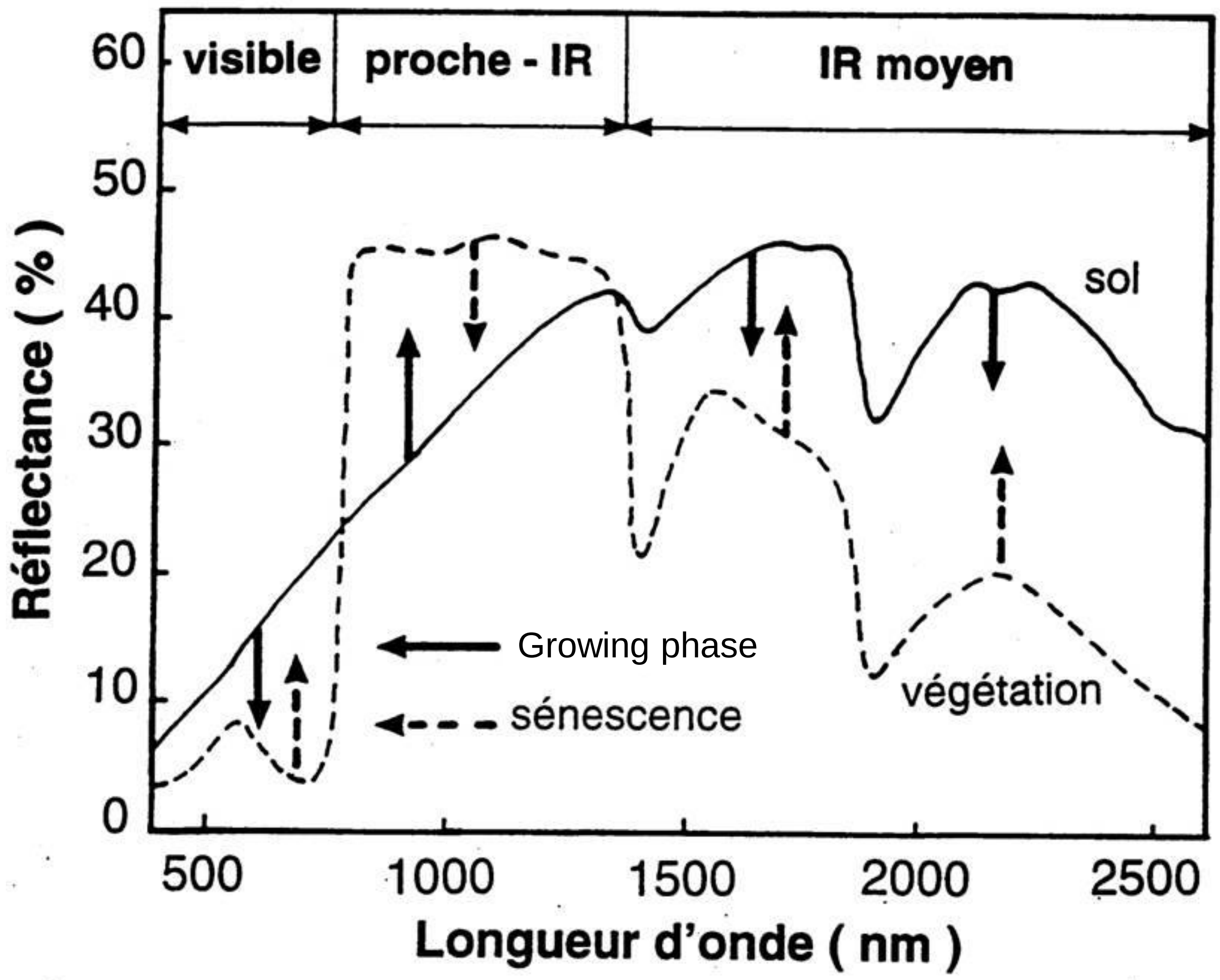
But usually very low temporal revisit, difficult to analyse seasonnal vegetation dynamics for instance.



Leaf optical proprieties



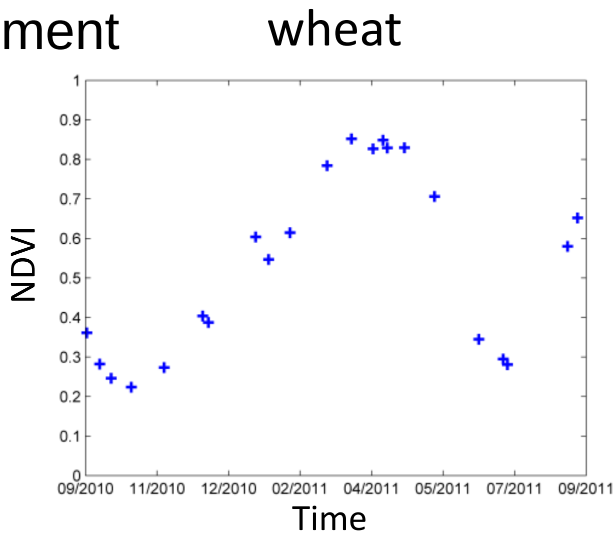
Effect of phenology on reflectances

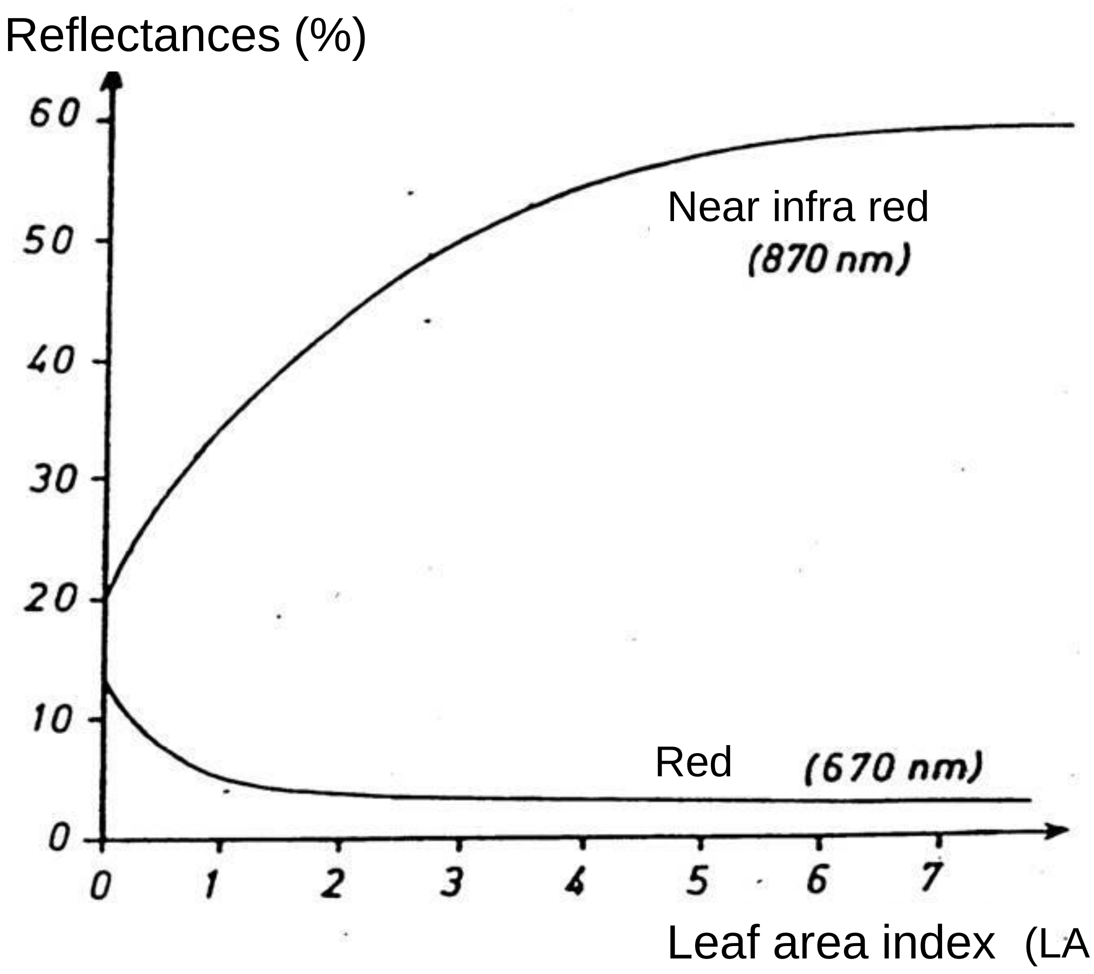


Normalised vegetation index (NDVI)

NDVI is a good proxy of the vegetation development

NDVI = (PIR-R)/ (PIR+R)   [-1,1]





Used for analysis of phenology

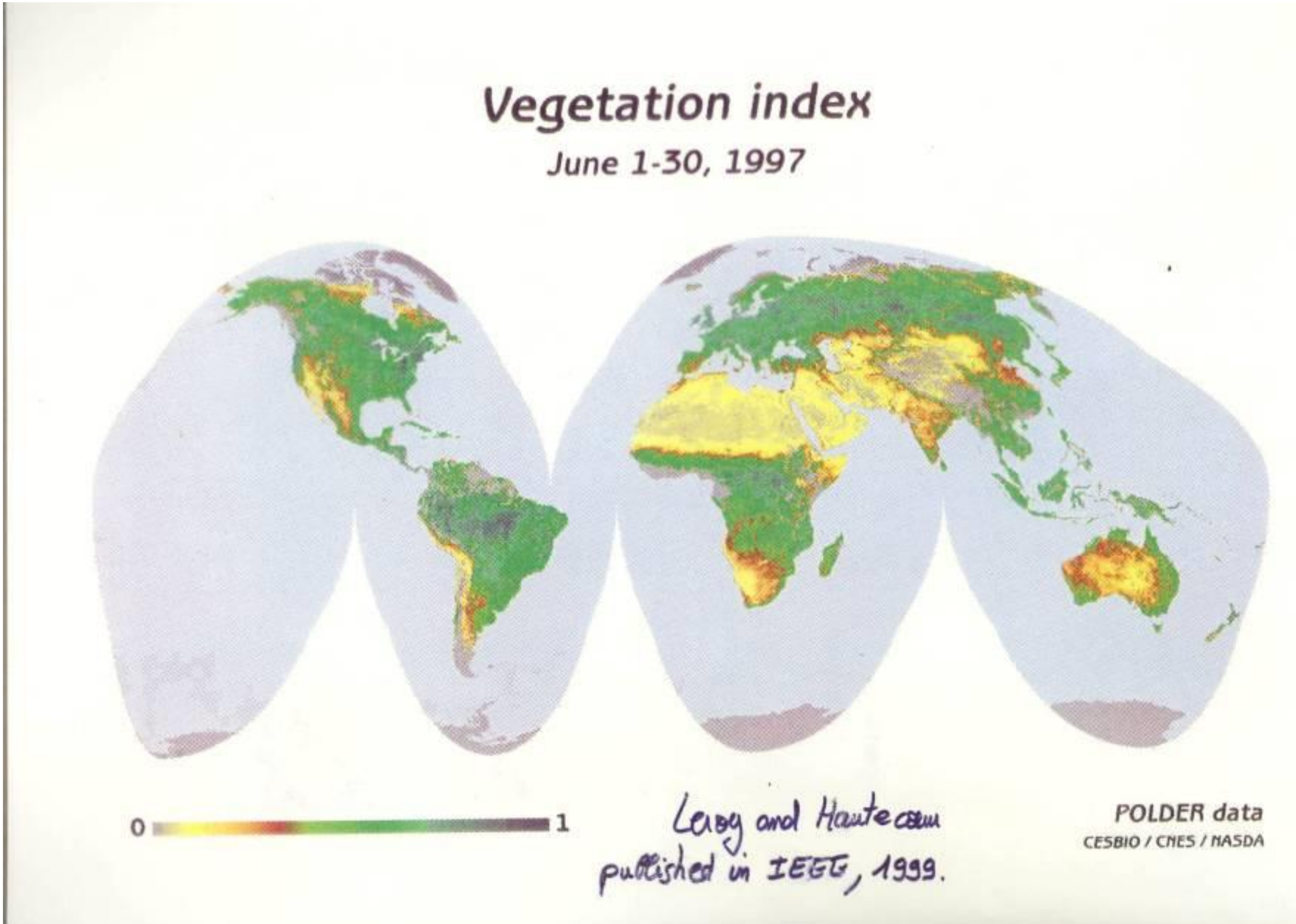
Desertification/ greening = f (interannual climatic variability)

Afforestation/deforestation

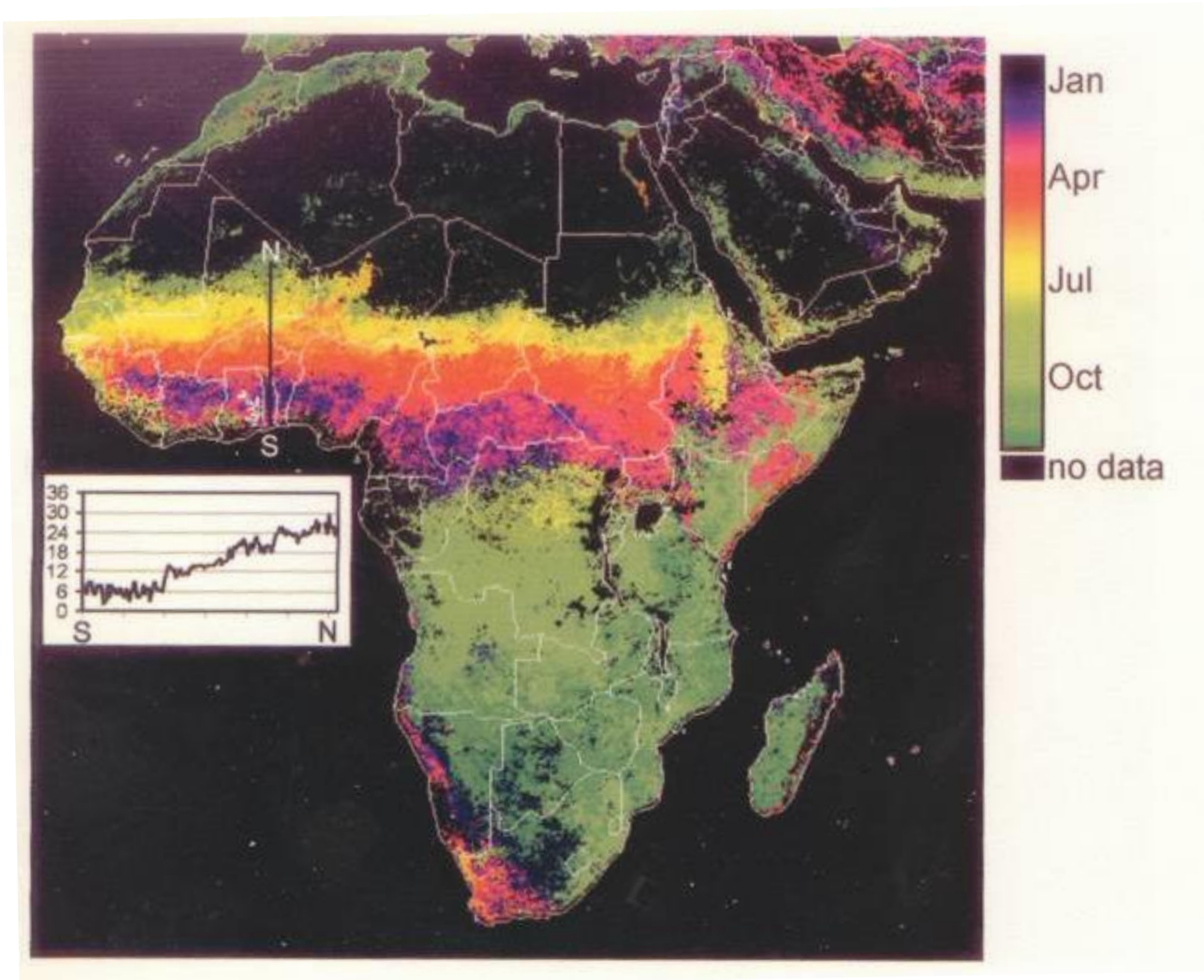
Direct assimilation in the models

…

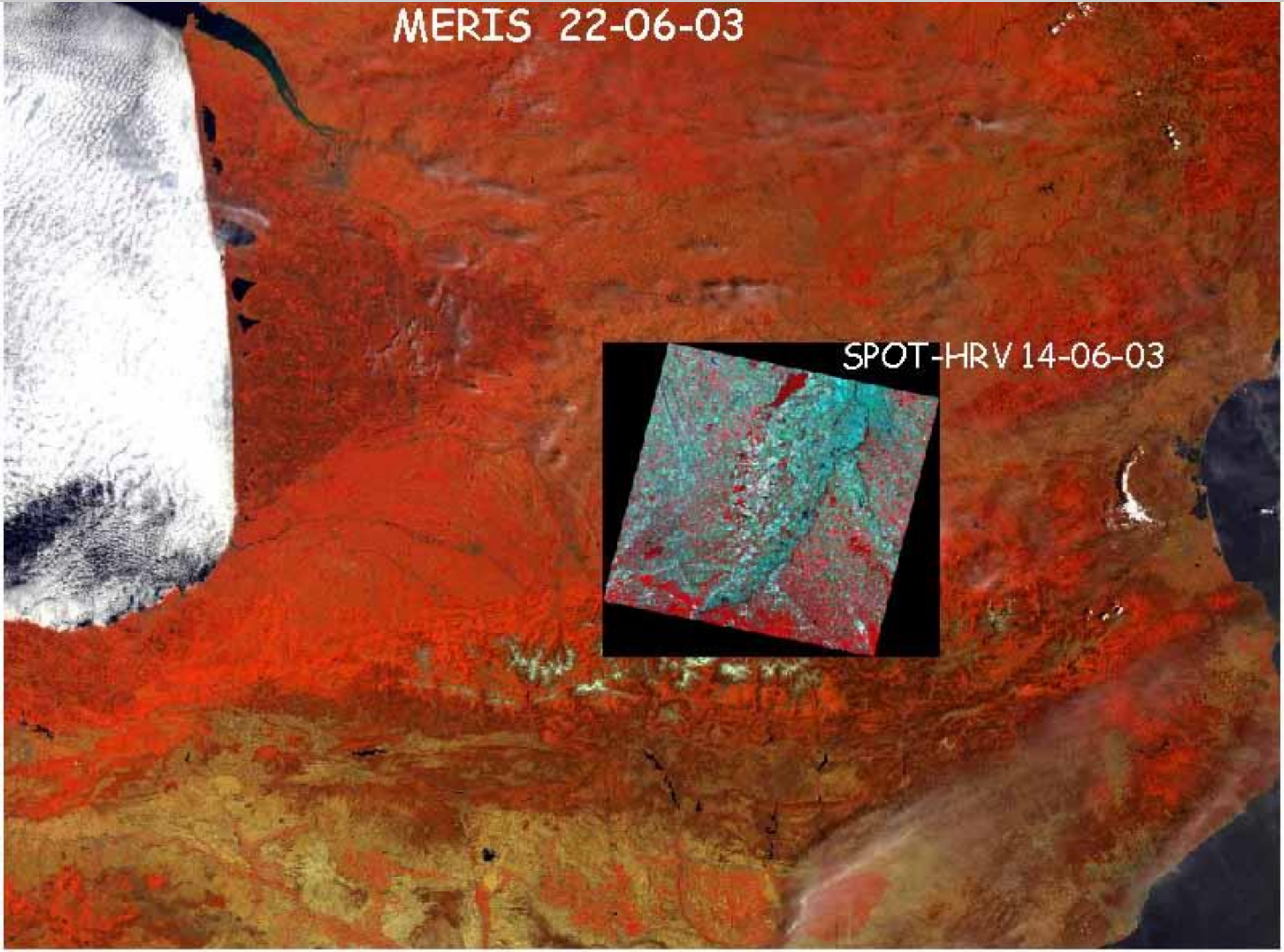
Global mapping of NDVI



Estimating start of growing season from NDVI analysis



Effect of spatial resolution on the accuracy (class description/location) of land use maps



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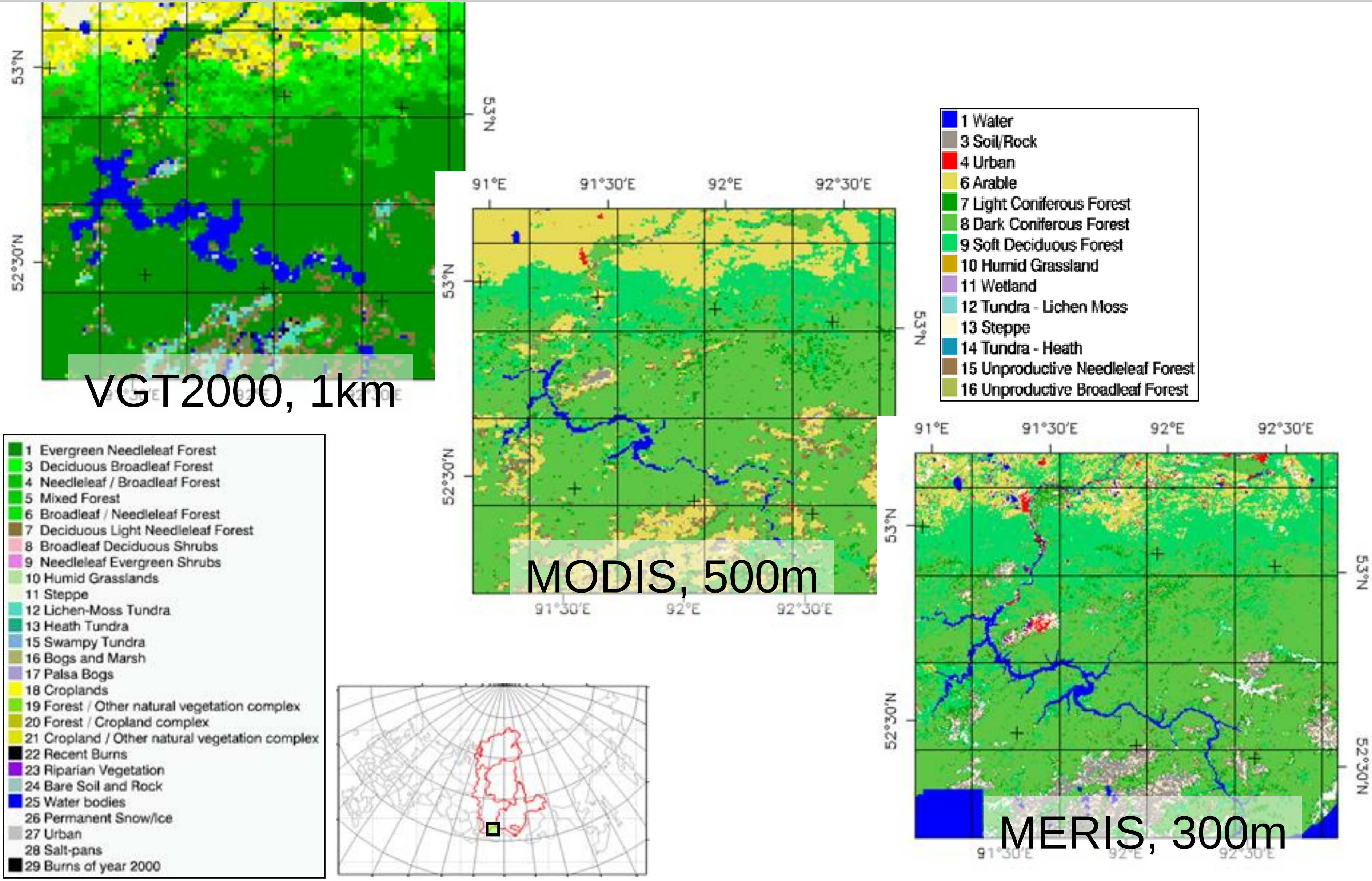
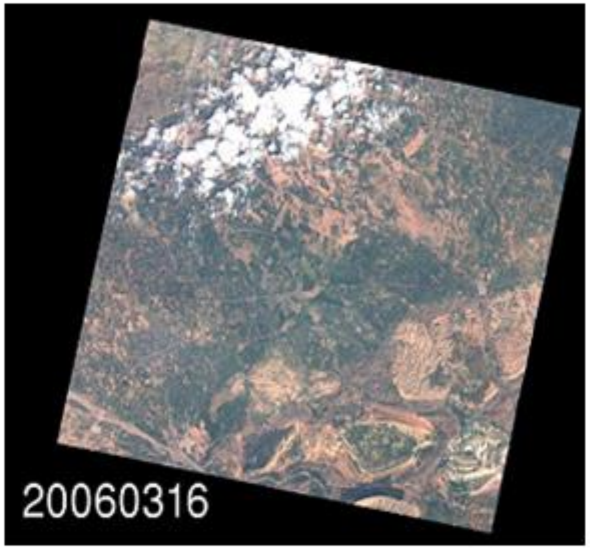
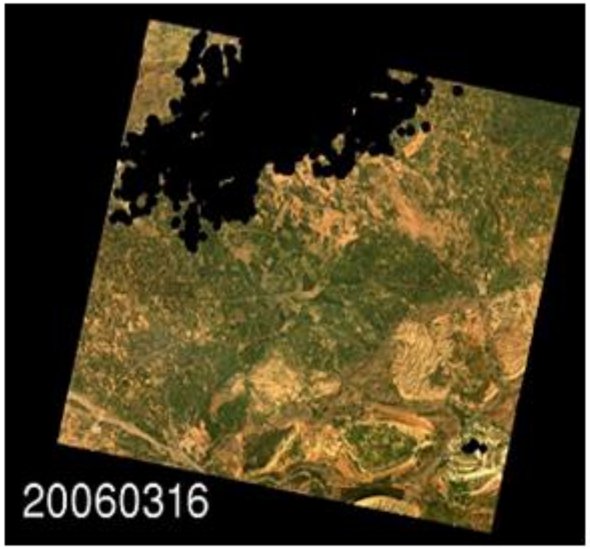


Image processing & product levels

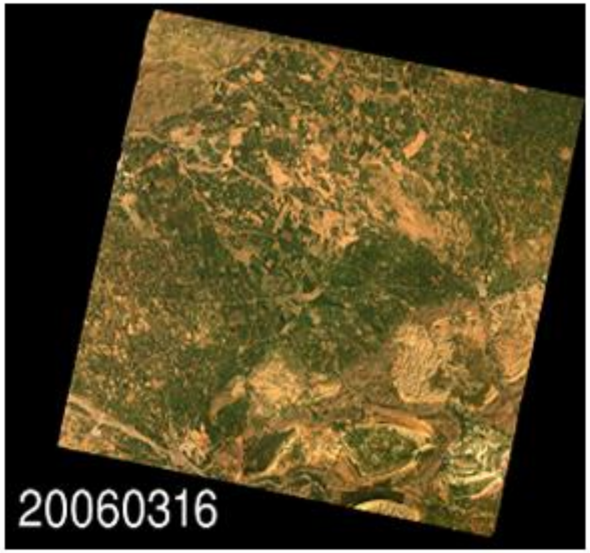
- Level 1C is a monodate ortho-rectified image expressed in TOA reflectance
- Level 2A is a monodate ortho-rectified image expressed in surface reflectance, provided with a cloud/cloud shadow/snow/water mask
- Level 3A is a monthly composite of Level2A Cloud/Cloud shadows free pixels



Level 1C:



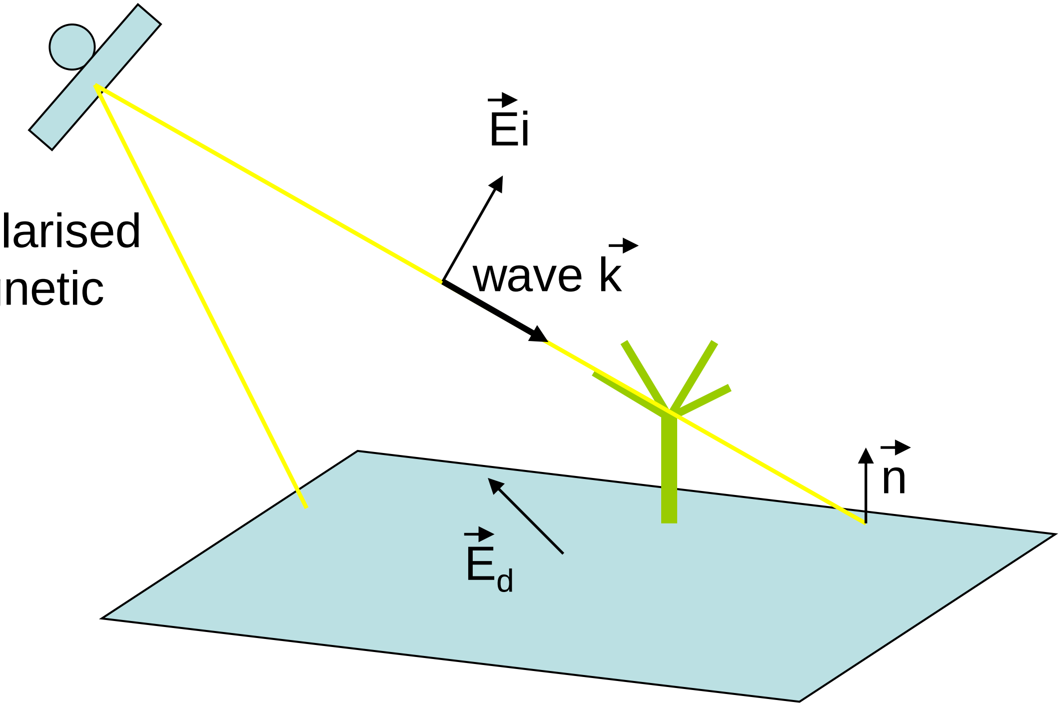
Level 2A:



Level 3A:

Some basis concerning radar RS

Radar:



Incident polarised electromagnetic wave

The electromagnetic wave has an electric filed $\vec{Ei}$ and an incidence plan defined by $\vec{k}$ et $\vec{n}$

If $\vec{Ei}$ is part of the incidence plan, the signal has a vertical polarisation, if it is perpendicular to the plan, then the polarisation is horizontal (controled by the source)

Some basis concerning radar RS

The soil is defined by a matrix of diffusion [S] qui lie le champ incident $\vec{E}_i$ au champ diffusé $\vec{E}_d$

$$\vec{E}_d = a\,[S]\,\vec{E}_i \quad \text{or} \quad \begin{pmatrix} E_D^V \\ E_D^H \end{pmatrix} = a * [S] * \begin{pmatrix} E_i^V \\ E_i^H \end{pmatrix}$$

Therefore we talk for instance about radar retrodifusion HH (pour HiHd)

Different radar antennas exist :

- with simple polarisation : HH or VV
- with double polarisation (ex: ENVISAT) : HH & HV, or VV & VH, or HH & VV

Some basis concerning radar RS

Ratio are also defined (coefficients of retrodiffusion)

- of copolarisation $$\rho_1 = \frac{HH}{VV}$$

- of crosspolarisation $$\rho_2 = \frac{HH}{HV}$$ ou $$\rho_3 = \frac{VV}{VH}$$

For the soil $H_d > V_d$, for the vegetation $V_d > H_d$

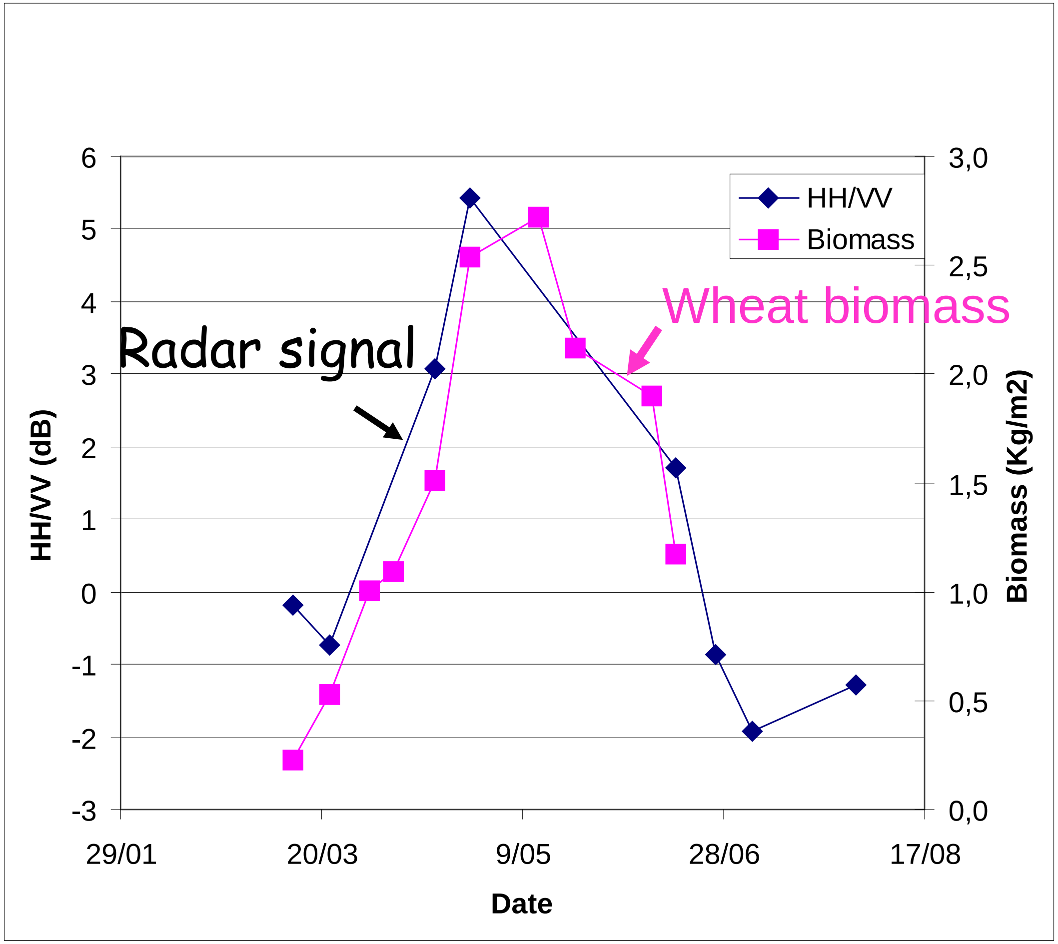
The coefficient of retrodiffusion is sensitive to soil and vegetation water content

SAR data near Toulouse (France)

ASAR, dual polarisation, May 3rd 2003
RGB: VV- HV- VV

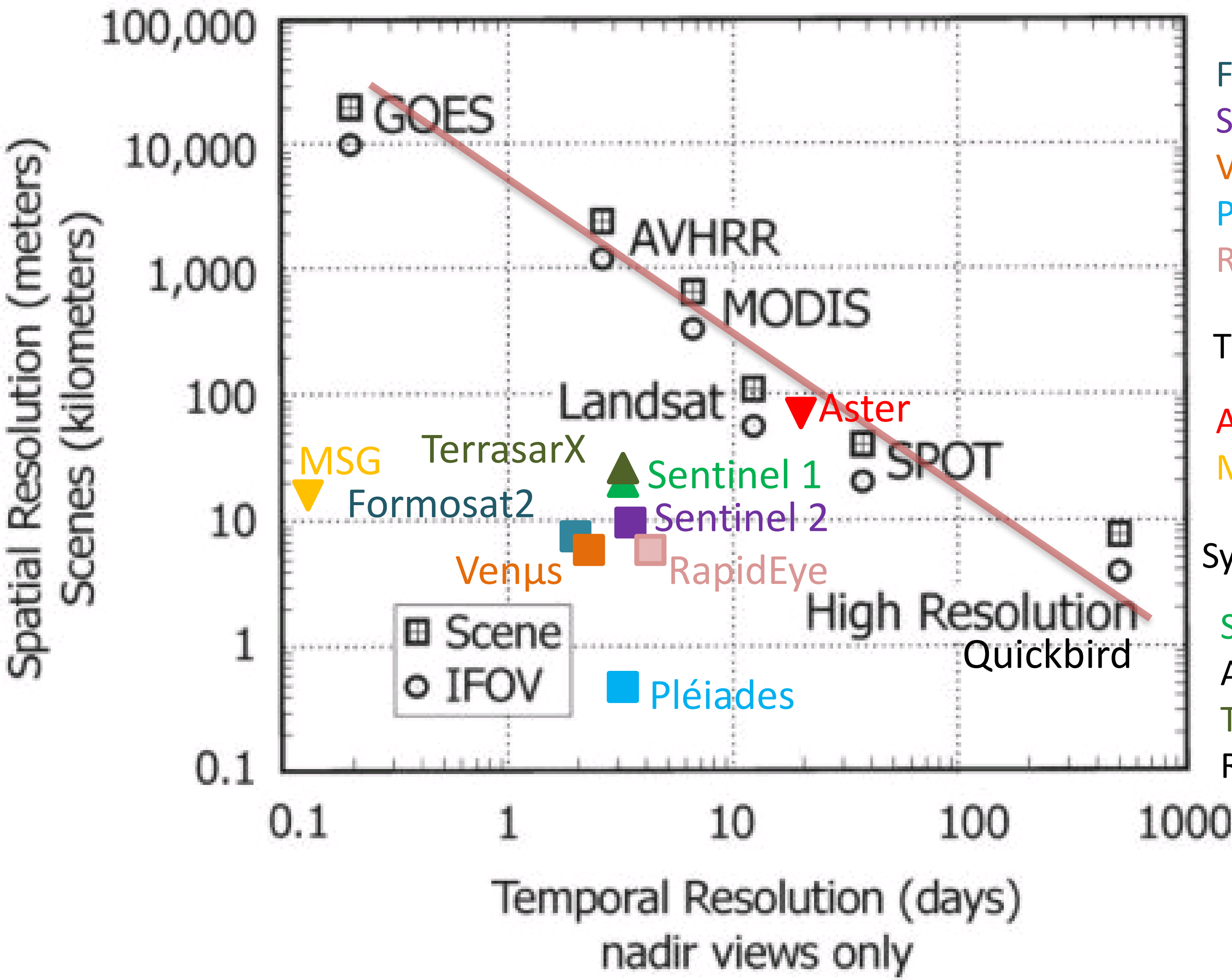
The retrodiffusion in cross polarisation (HV, in green) corresponds to a strong diffusion due to the volume of winter crops (mainly wheat and rapeseed). In purple bare soil (future summer crops).

Lamasquère site observed with ENVISAT



Spatial vs temporal resolution

For a long time compromises between temporal and spatial resolution had to be done



Optical remote sensing

Formosat 2 : B, G, R, NIR
Sentinel 2 : B, G, R, NIR, SWIR
Venµs : 12 bands (415-910 nm)
Pléiades : B, G, R, NIR
Rapideye : B, G, R, NIR, Redge

Thermic

Aster : 90m, 16 days
MSG : 4 km, 15 min

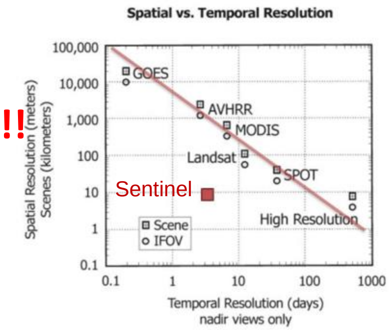
Synthetic aperture radar (SAR)

Sentinel 1 : band C
Alos : band L 10-100 m
TerrasarX : band X 1-20 m
Radarsat 1&2: banc C 1-100m

The exemple of the Sentinel 1 & 2 satellites

Sentinel 1
(10 m, 6j, SAR)

A revolution !!!

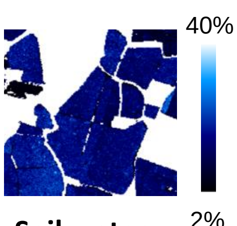


Sentinel 2
(**10 m, 5j, Optical**)

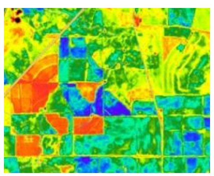
Clear sky or cloudy conditions
Rugosity & surface humidity

measured parameters

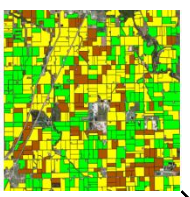
Clear sky conditions
Reflectances



Soil water content



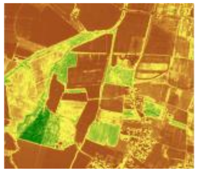
Biomass



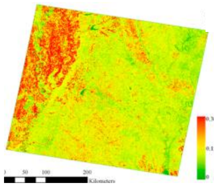
Soil work

Dynamic mapping

Land use



Leaf area index/ phenology



Albedo ??

fusion

How can we use this wealth of information to answer scientific and societal questions?

A dynamic vision of cropland status

The importance of high spatial and temporal resolution for accurate crop monitoring (mapping, production) and farming operations,

Satellite
Formosat 2
(résolution 8m)

- West et al. (2010) showed that medium resolution (MODIS) did not allow for a sufficiently accurate identification of crop classes (just 2 classes) and an accurate estimation of CO_2 fluxes, C and GHG balances

A dynamic vision of cropland status

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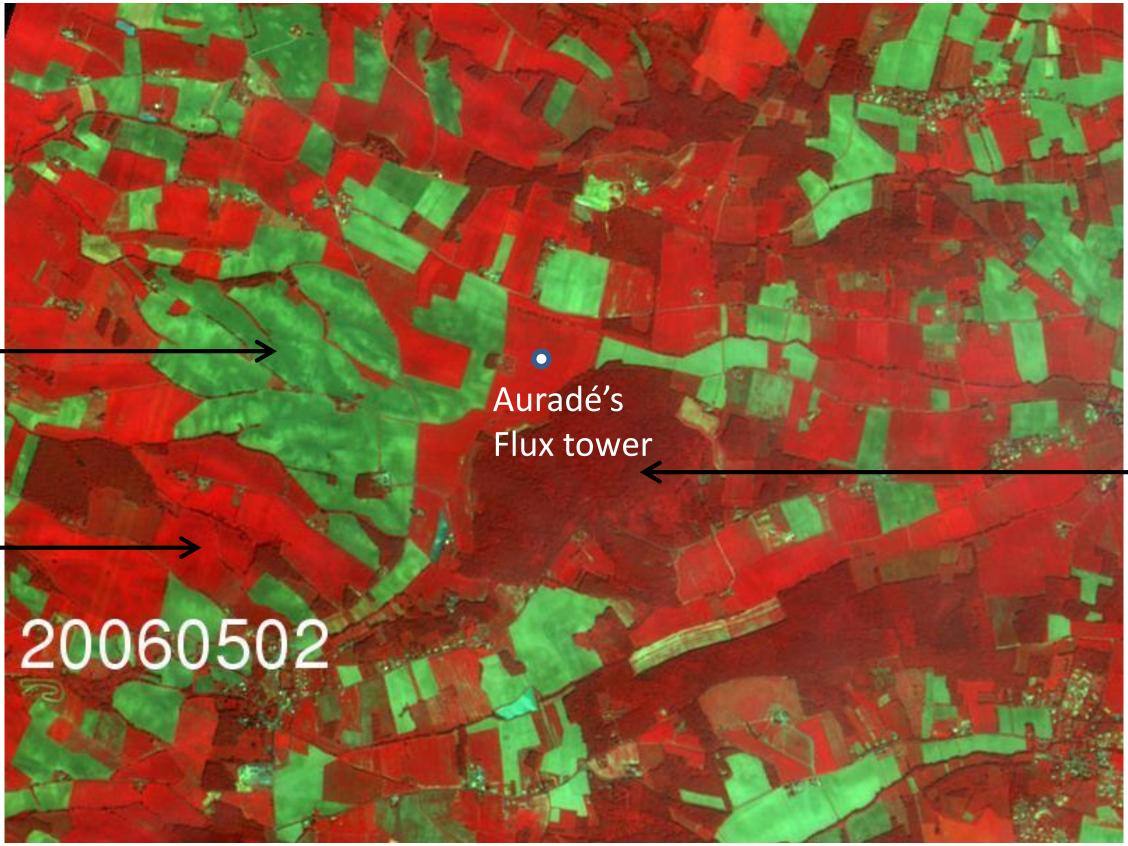

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Formosat 2

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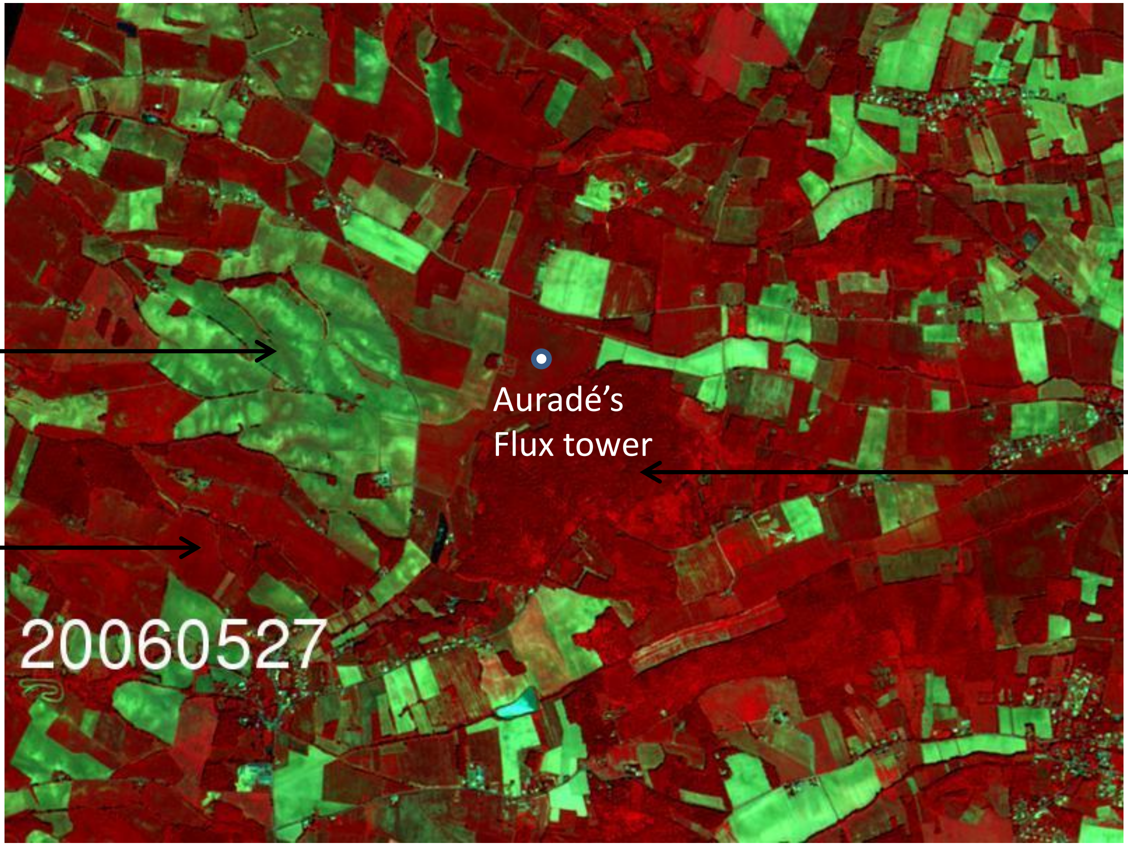

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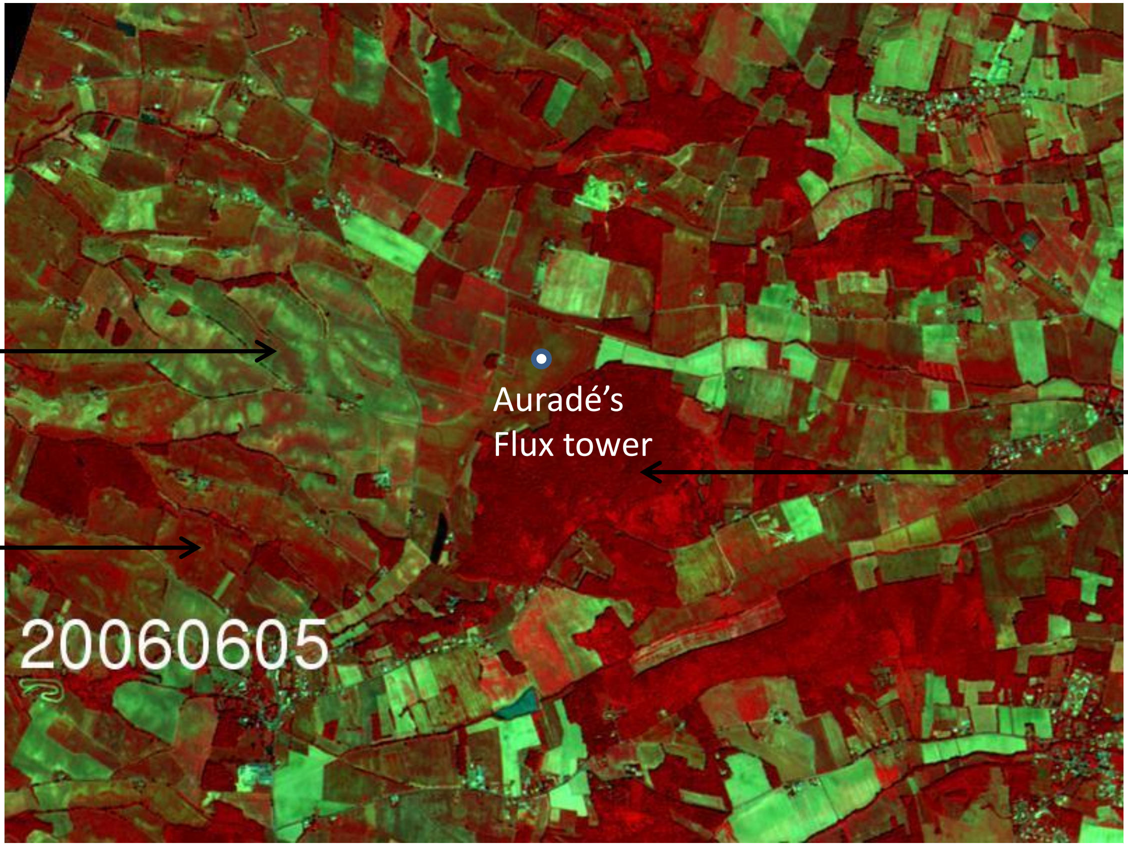

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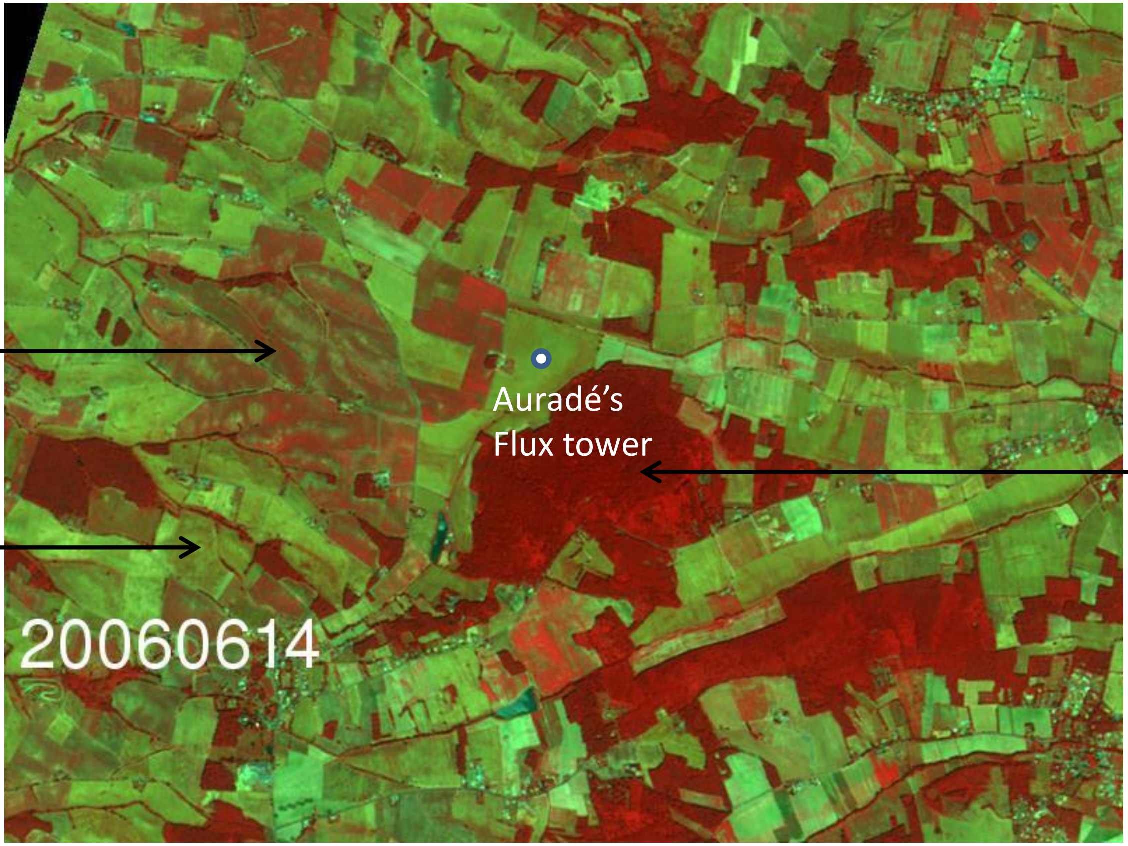

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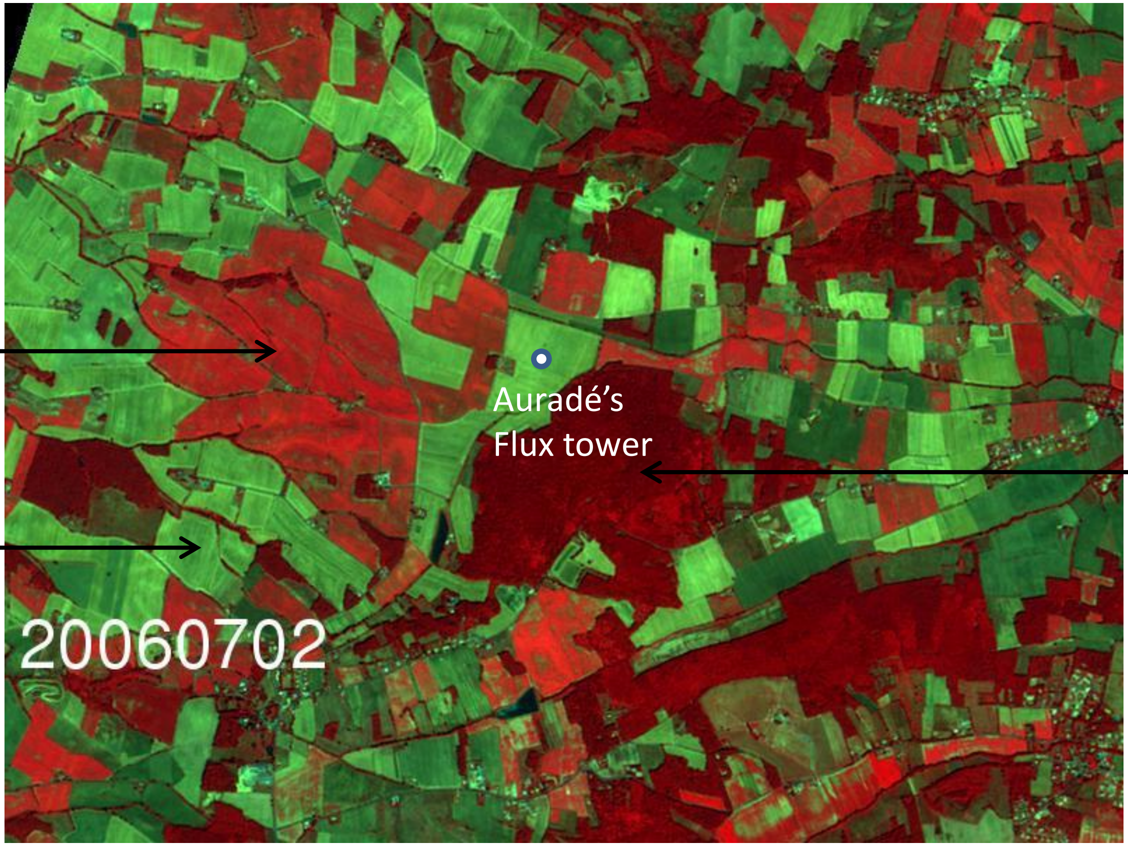
Satellite
Formosat 2



Sunflower

Active forest

Harvested wheat

- West et al. (2010) showed that medium resolution (MODIS) did not allow for a sufficiently accurate identification of crop classes (just 2 classes) and an accurate estimation of CO_2 fluxes, C and GHG balances

A dynamic vision of cropland status

The importance of high spatial and temporal resolution for accurate crop monitoring (mapping, production) and farming operations,

Satellite
Formosat 2

Sunflower

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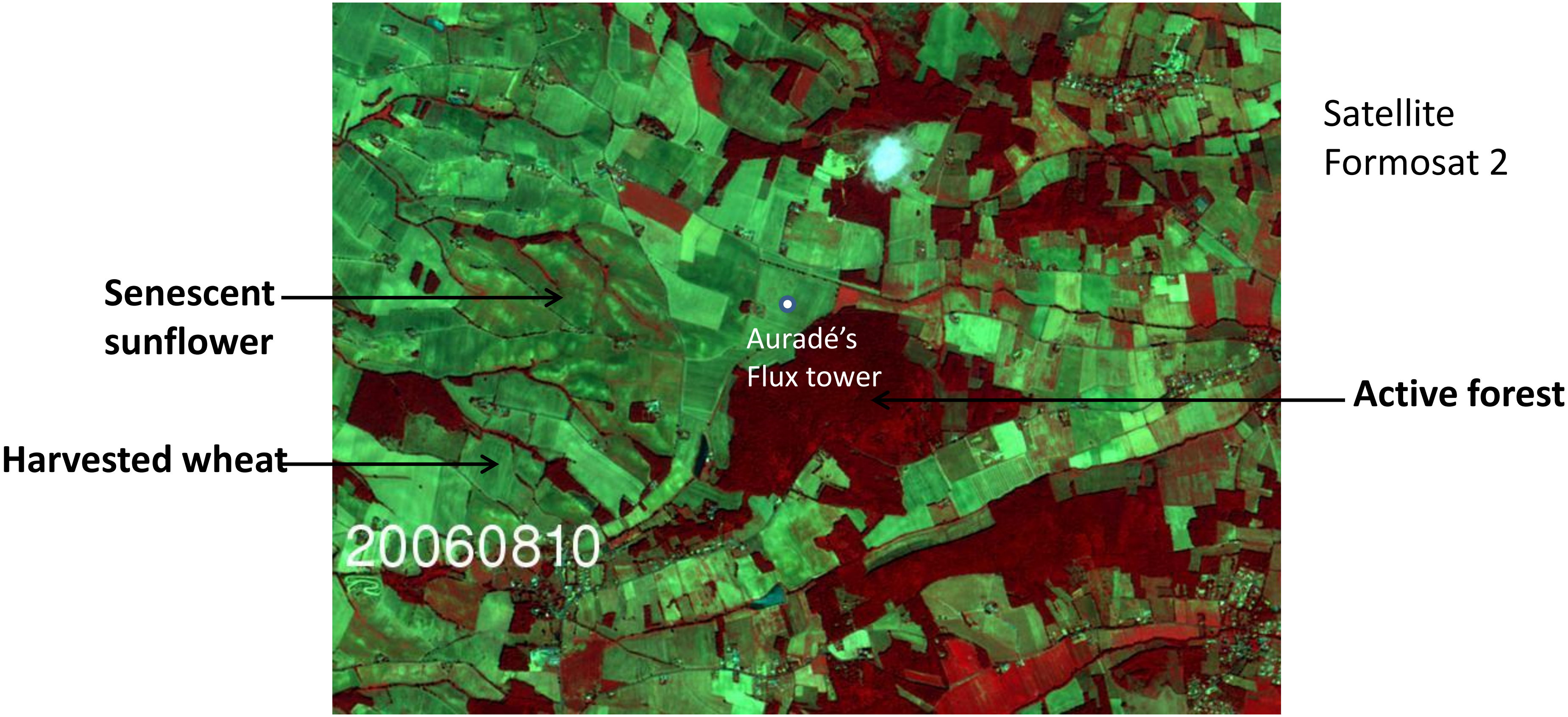

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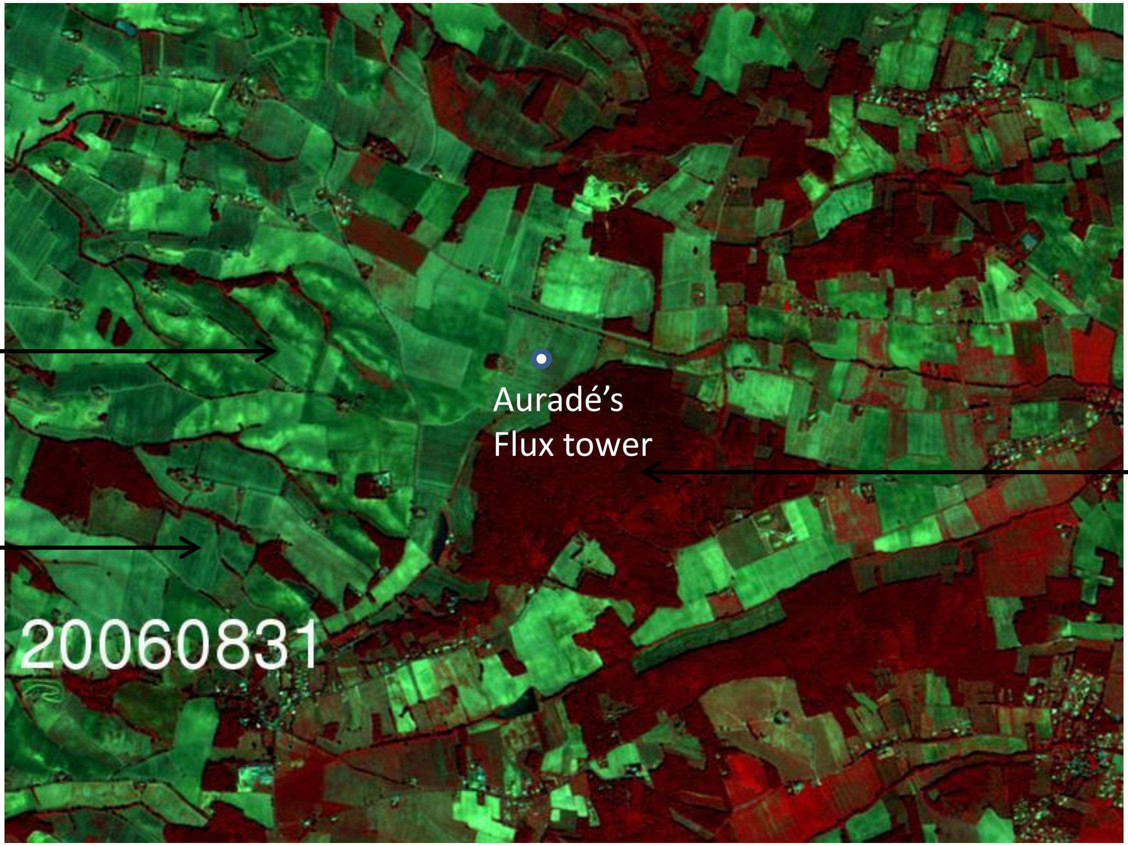

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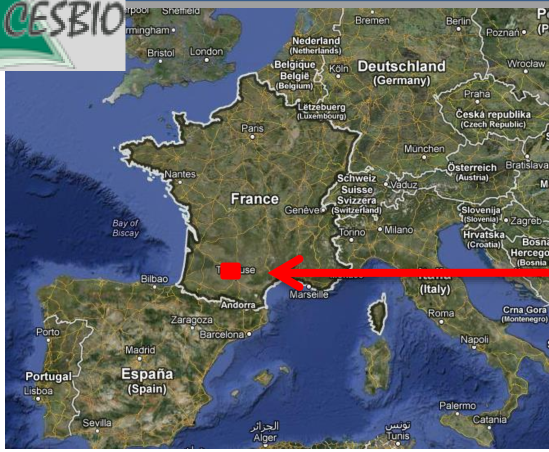
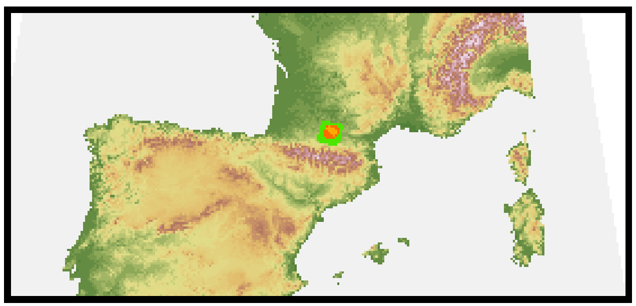
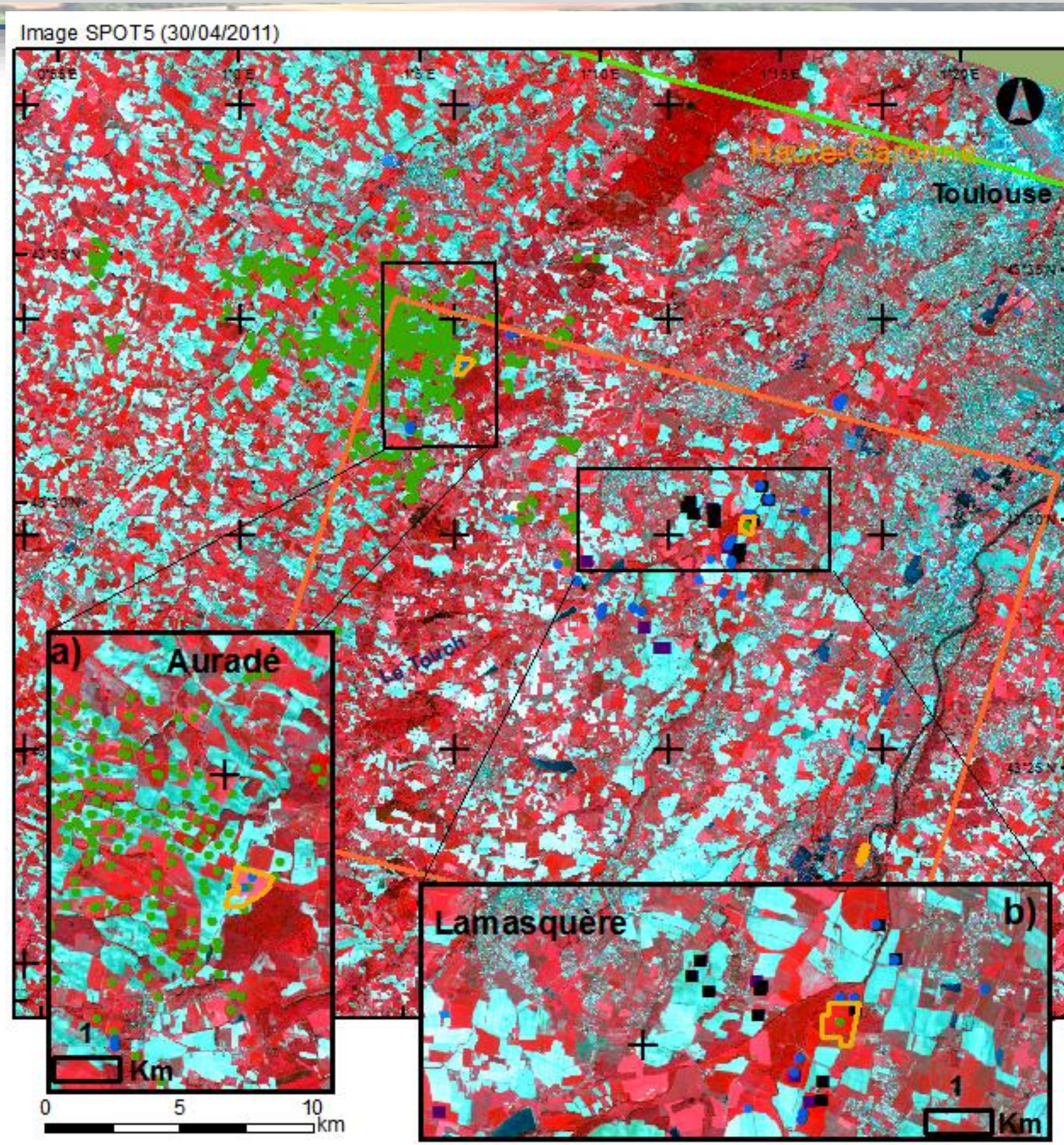
Case study: the Regional Space Observatory (France)







Experimental Sites (2004...)

ESU — Biomass & Yield Data (2011)

Yield Data (farmers surveys)

ESU — LAI & Biomass Data (2008)

LAI & Biomass Data (2010)

SAFRAN grid

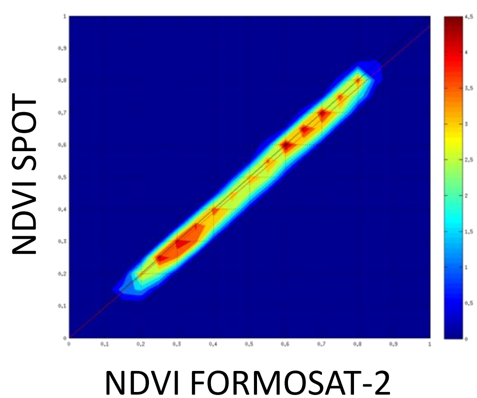
SPOT window (depuis 2002)

Formosat-2 window (depuis 2006)

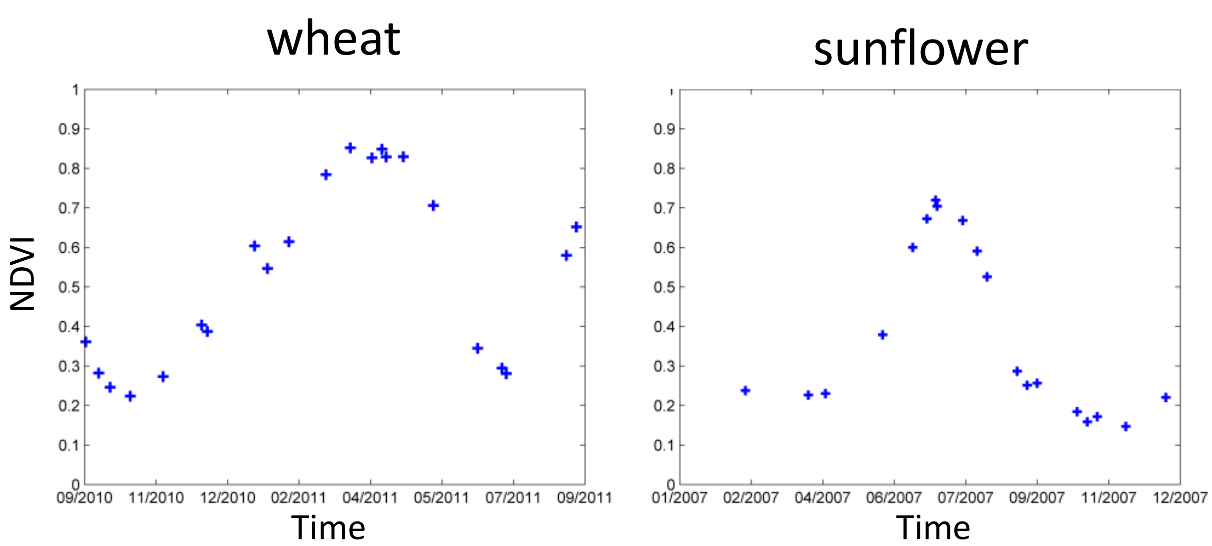
Optical remote sensing at RSO

Multi-sensors: Formosat-2 & Spot (2,4,5) : more than 250 images between 2006 and 2011… much more since 2016 with Sentinel 2

$$NDVI = \frac{NIR - RED}{NIR + RED}$$



Multi-temporal series

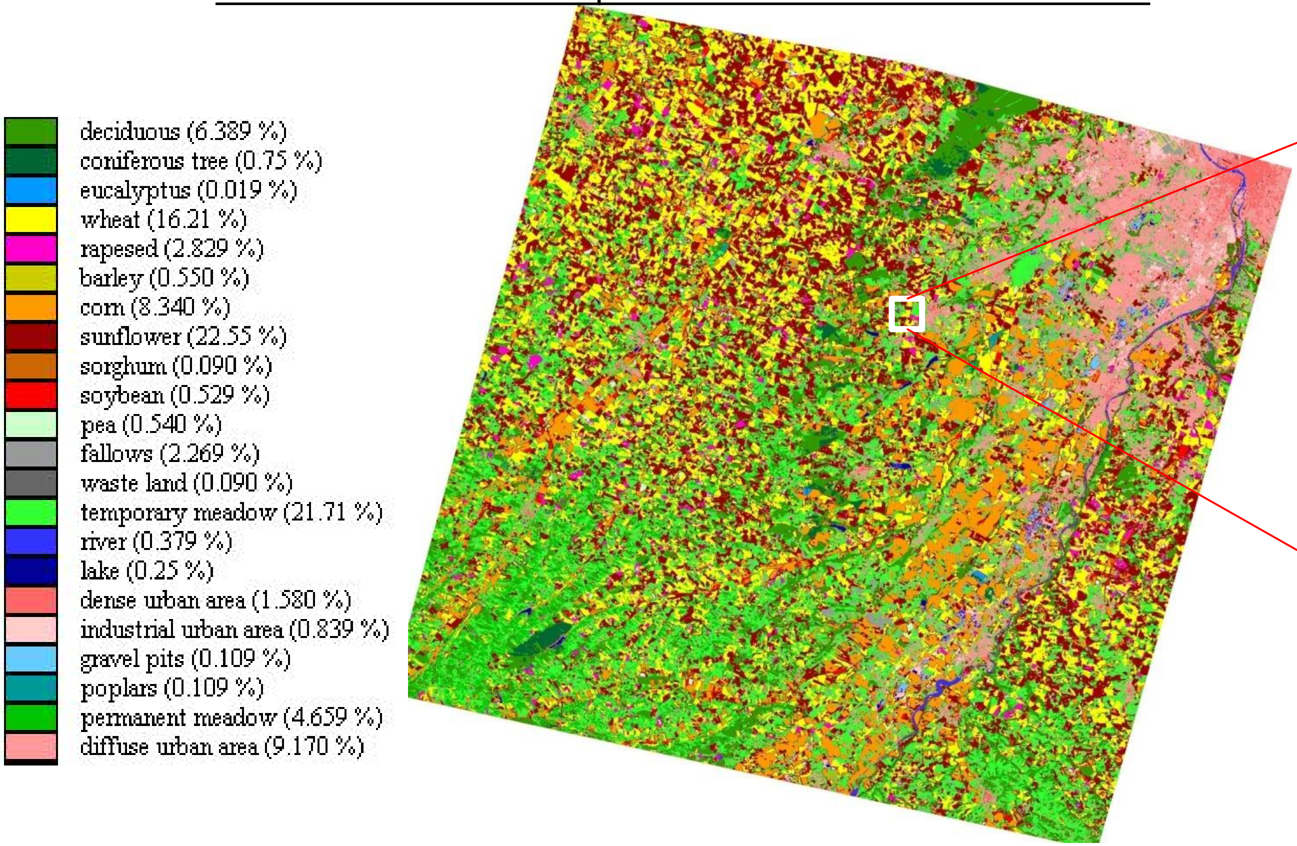


Detailed land use maps used for spatial crop modelling

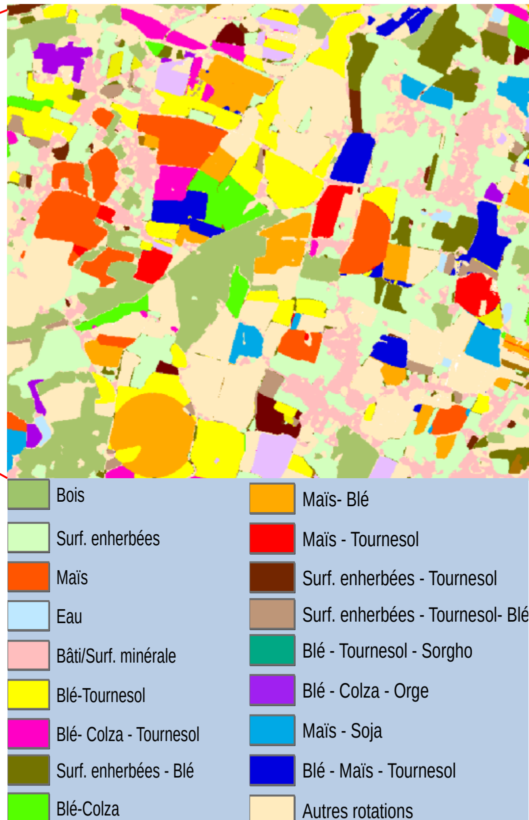
Possible thanks to high spatial resolution optical multi-temporal images:

- 21 classes in total,
- - 8 crop classes + subclasses including grain maize and silage (very different C exports)

<u>8 to 20m resolution map in 1992 and between 2001-2014</u>



Crop rotation map at 10m between 2006-2012

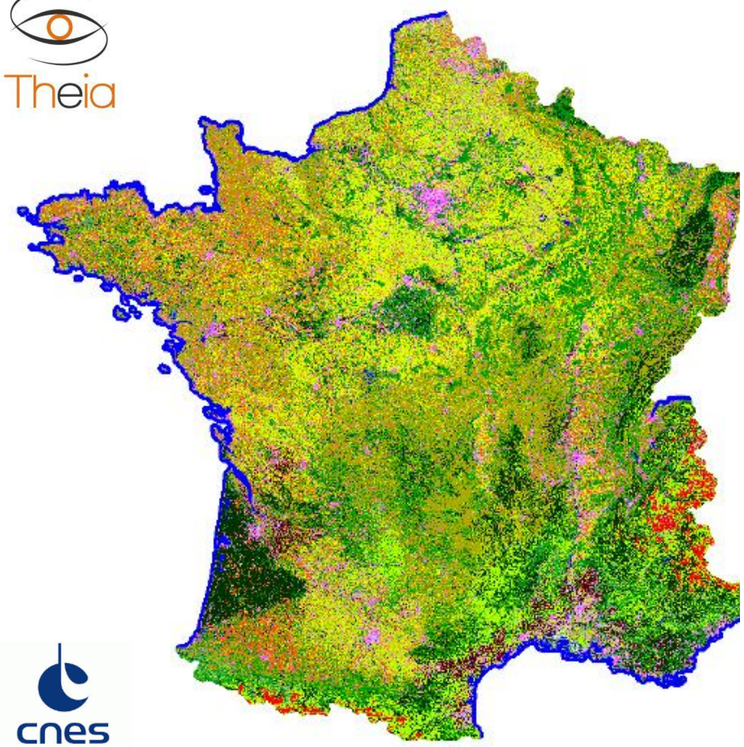


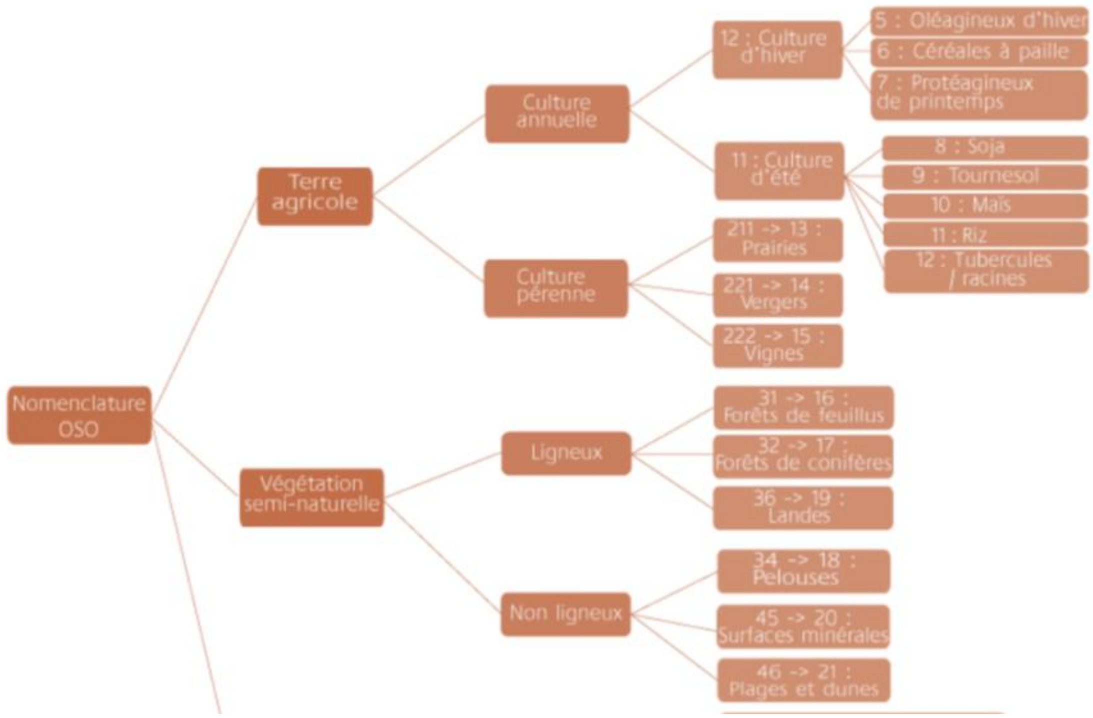
Dejoux, JF., Ducrot D., P. Gouaux, Inglada J., Marais-Sicre C., Masse A., Valero S.

Detailed land use maps used for spatial crop modelling

- Annual land use mapping for France (THEIA OSO) at 20 m resolution with IOTA²: enrichment of crop classes since 2018 (7 classes)
- Part of this methodology has been integrated in the SEN4CAP tool for the CAP monitoring

Theia





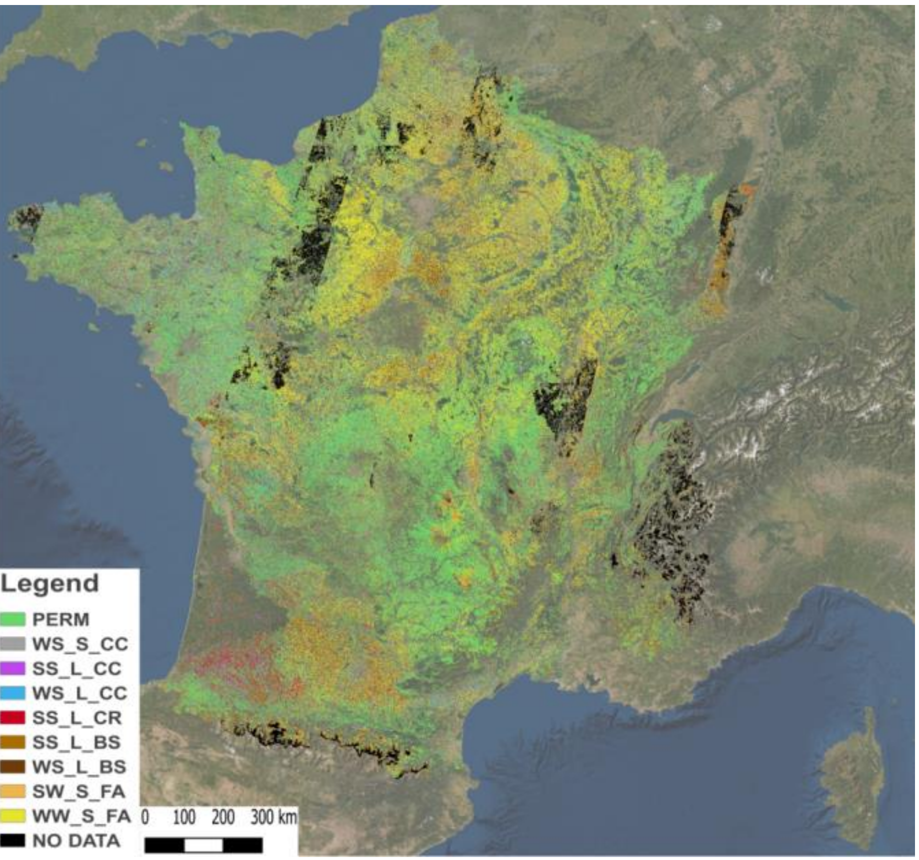
cnes
CENTRE NATIONAL D'ÉTUDES SPATIALES

Inglada J., Thierion V., Fauvel M.

Mapping of agricultural practices

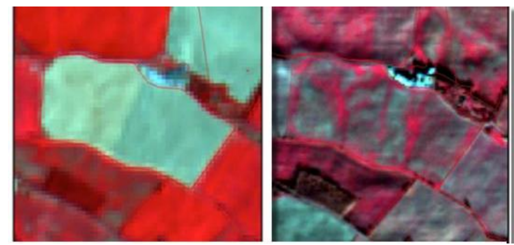
→ To respond to a wide range of agro-environmental issues; climate mitigation, water management (irrigation needs), air quality (aerosols), erosion (soil work), diseases (presence of surface crop residues), etc.

→ Need to establish an initial diagnostic (current practices and their evolution)



Mapping of cover crops (collab. CNES KERMAP/CESBIO

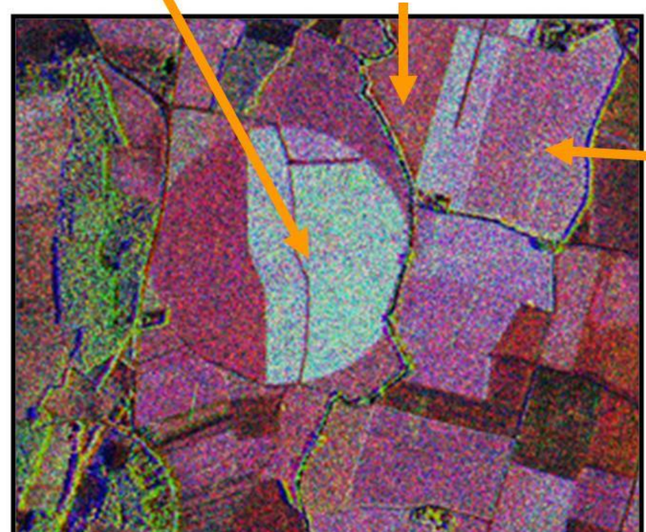
Is cover crop seeding successfull ?



…and how much C has been stored ?

Ploughing (high rugosity)

Smooth soil prepared for seeding



Superficial soil Work following ploughing (medium rugosity)

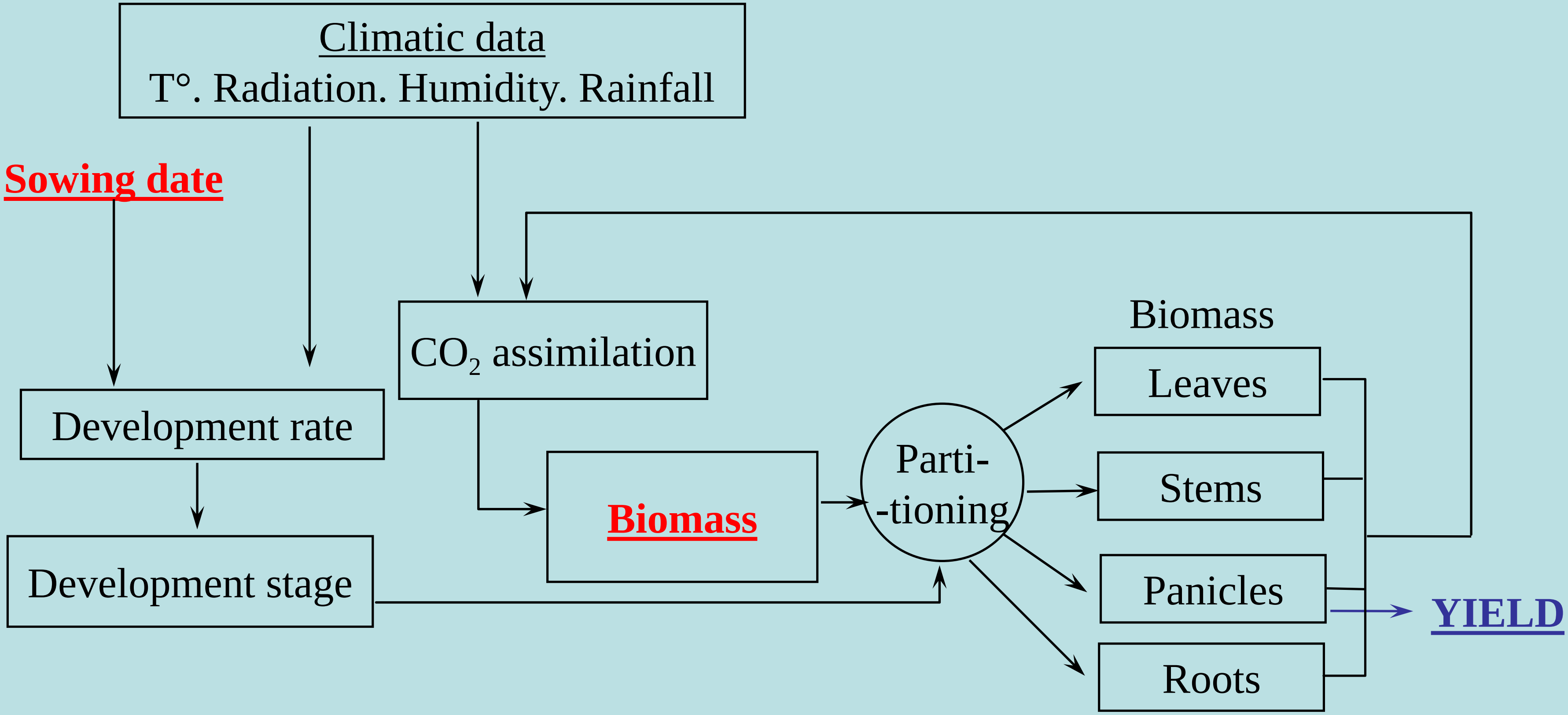
Source F. Baup, R. Fieuzal

Based on Terrasar X data

How to combine crop modelling and remote sensing to quantify spatio-temporal variability in crop production (biomass, yield), water & C fluxes/budgets and analyse the effect of crop management changes (e.g. cover crops vs bare soil)?

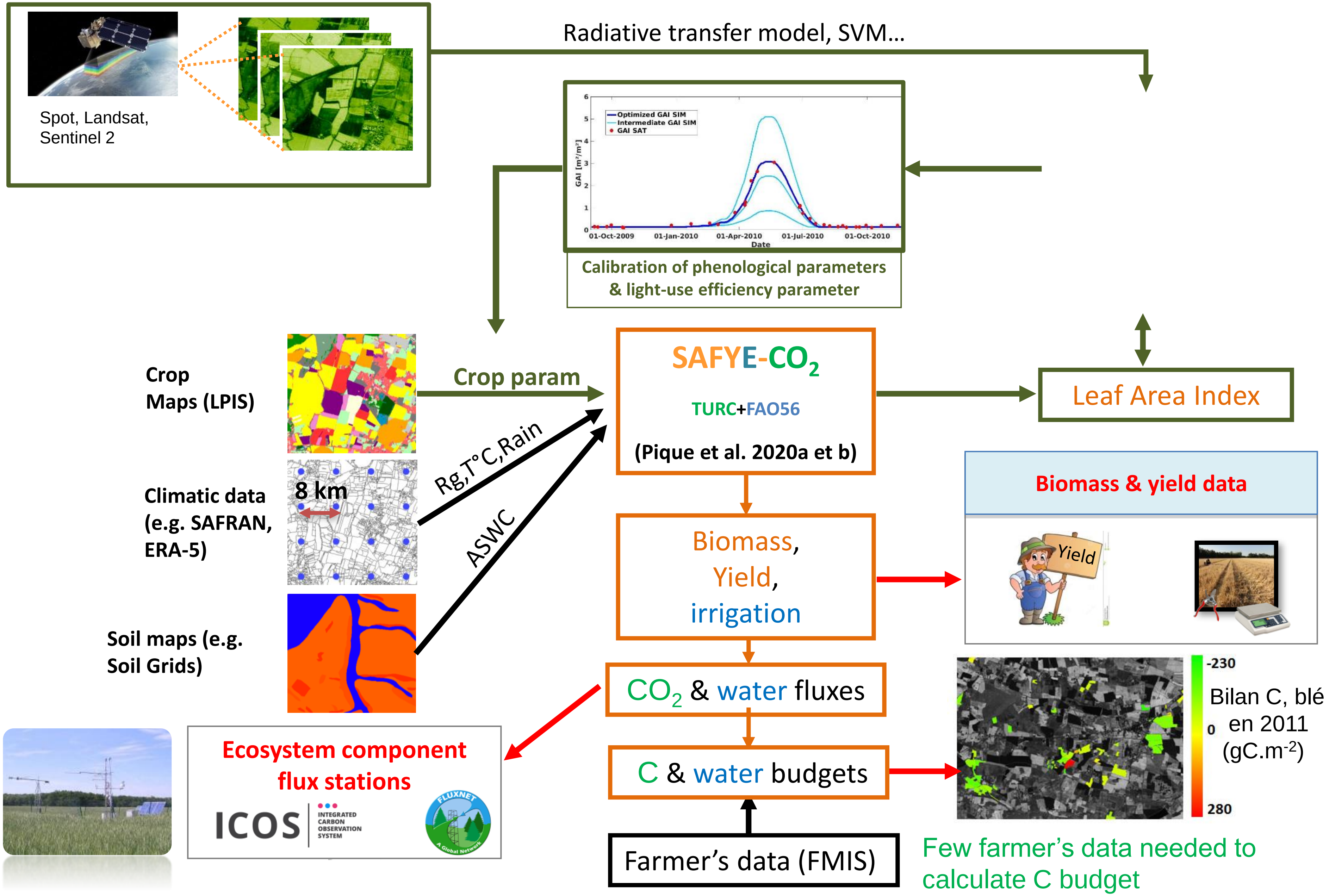
Exemple of SAR data assimilation in the Oryza crop model

(Ribbes et Le Toan, 1999): Oryza-1 model



- ➲ Sowing date ⟵ Radar Data (s° vs. Age)
- ➲ Biomass ⟵ Radar Data (s° vs. Biomass)

Modelling approach with SAFYE-CO_2



An evolution of the SAFY and SAFY-WB models

Model	Reference	Period of simulation	Simulated variables
SAFY	Duchemin et al. (2009)	Crop development	LAI, Aboveground Biomass, yield
SAFY-WB	Duchemin et al. (2015) ; Baup et al (2019)	Crop development	LAI, Aboveground & belowground Biomass, yield , E, TR, SWC, irrigation needs
SAFY-CO_2	Pique et al. (2020a) in GEODERMA	Cropping year (crop, fallow)	LAI, Aboveground & belowground Biomass, yield , photosynthesis (GPP), plant respiration (Ra), soil respiration (Rh), Ecosystem Respiration (Ra+Rh), C budget
SAFYE-CO_2	Pique et al. (2020b) in Remote Sensing	Cropping year (crop, fallow)	LAI, Aboveground & belowground Biomass, yield , photosynthesis (GPP), plant respiration (Ra), soil respiration (Rh), Ecosystem Respiration (Ra+Rh), C budget, E, TR, SWC.

CESBIO

Leaf area index [m^2/m^2]

Dry Biomass [kg/m^2]

Segment scale

Pixel scale

SAFY

500m

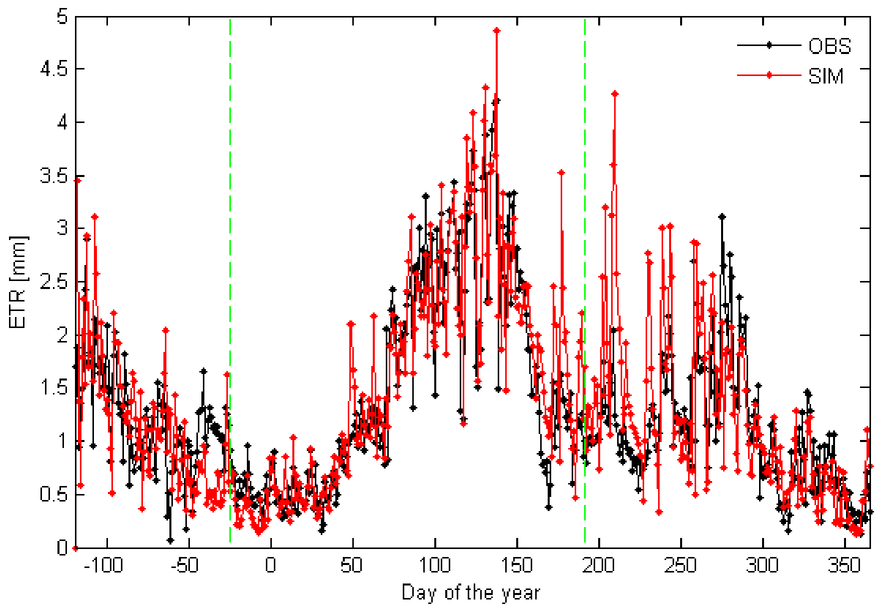
Derived from Formosat 2 (M. Claverie, V. Demarez, B. Duchem

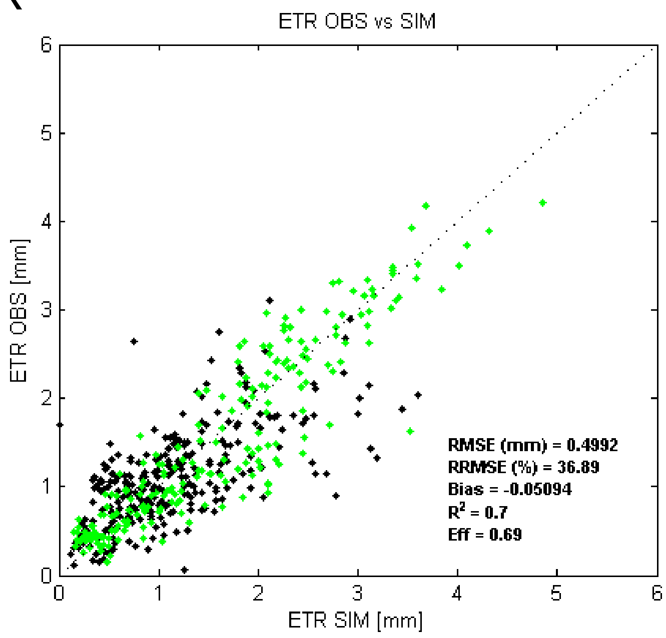
Estimating evapotranspiration with the SAFY-WB model

Study Case: winter wheat at the **Auradé Site, 2006**

See Duchemin et al. (2008) and Claverie et al. (2012) for a description of the water flux module

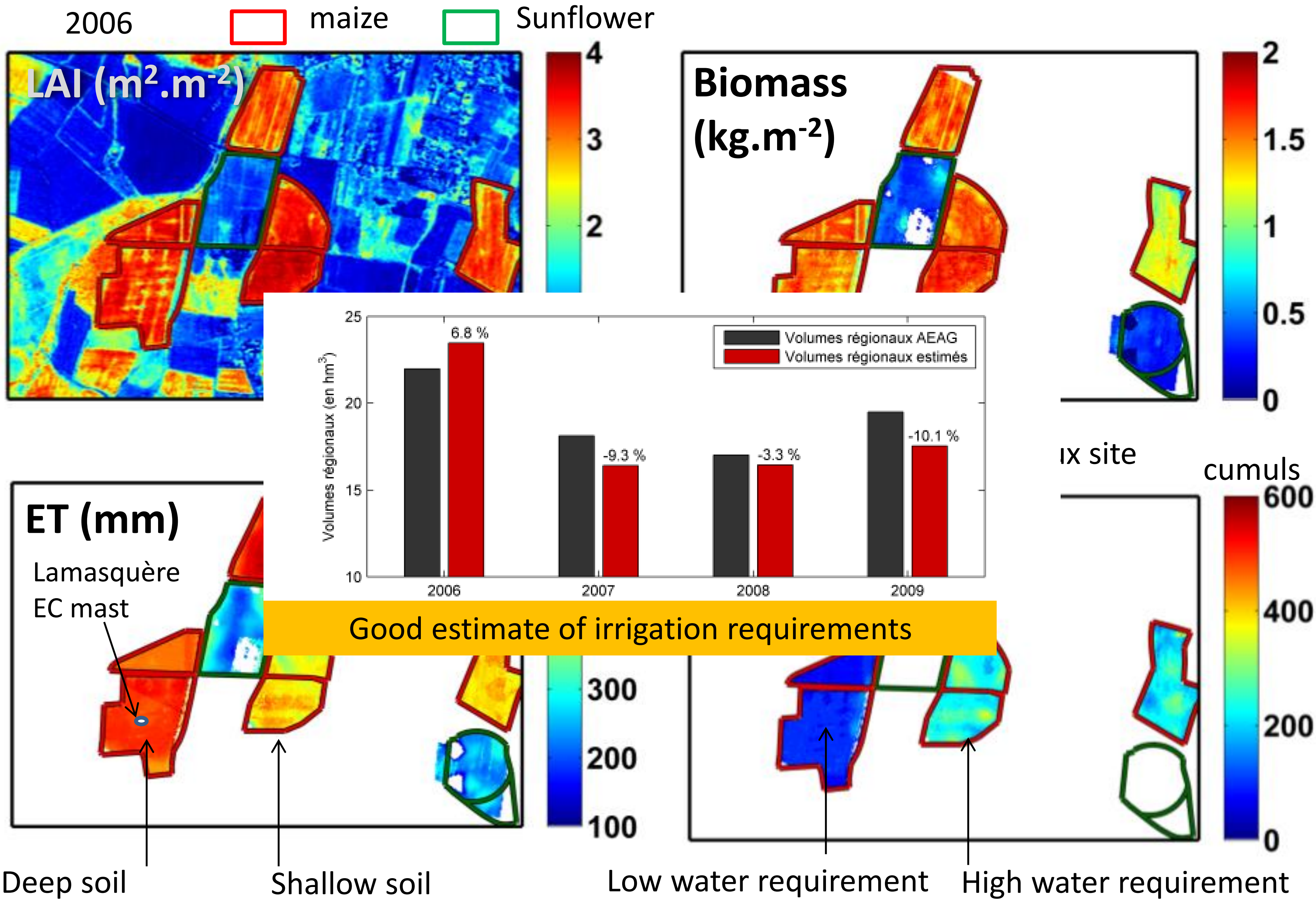
ETR





The previous version of the model had a quite good performance in estimating ETR (and SWC dynamics, not shown)

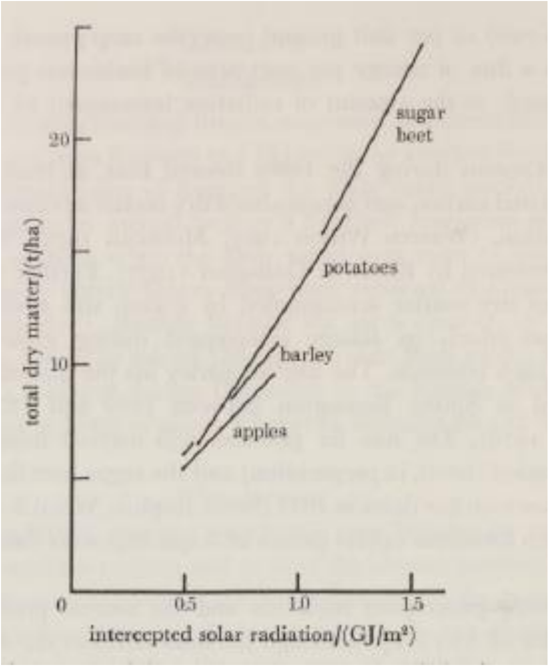
Exemple of simulation for summer crops



Differences in formalisms between

➔ between SAFY/SAFY-WB and SAFY-CO_2/SAFYE-CO_2 for estimating biomass production

In SAFY/SAFY-WB



Based on Monteith 1977 : found a linear relationship between **annual** biomass produced and intercepted radiation,

➔ Concept of LUE (Light Use Efficiency) that may vary between 0,1 and 0,7 gC/MJ APAR (from 0.40 to 0.52 according to Waring & Running, 1998)

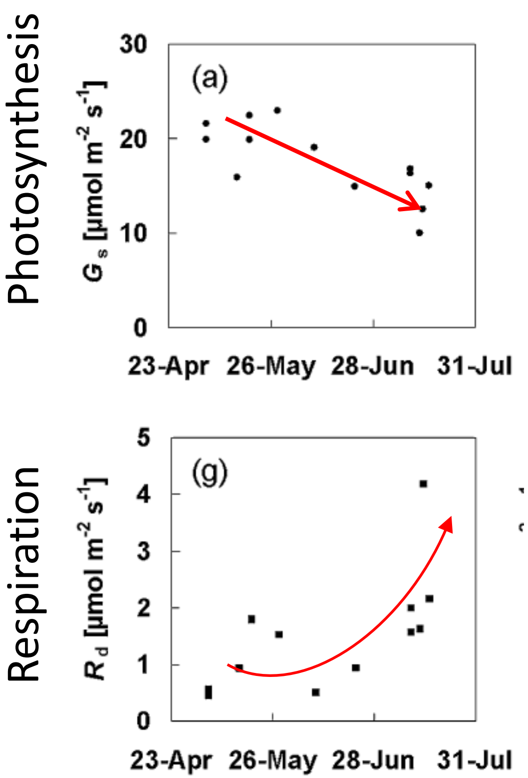
In SAFY/SAFY-WB calculated with the following equation but on a **daily time step** pas ➔ implicit hypotesis that the ratio photosynthesis/plant respiration is constant along the season as NPP = GPP- Ra

$$\Delta DAM \quad = Rg \times \varepsilon_c \times FAPAR \times ELUE \times Ft(Ta)$$

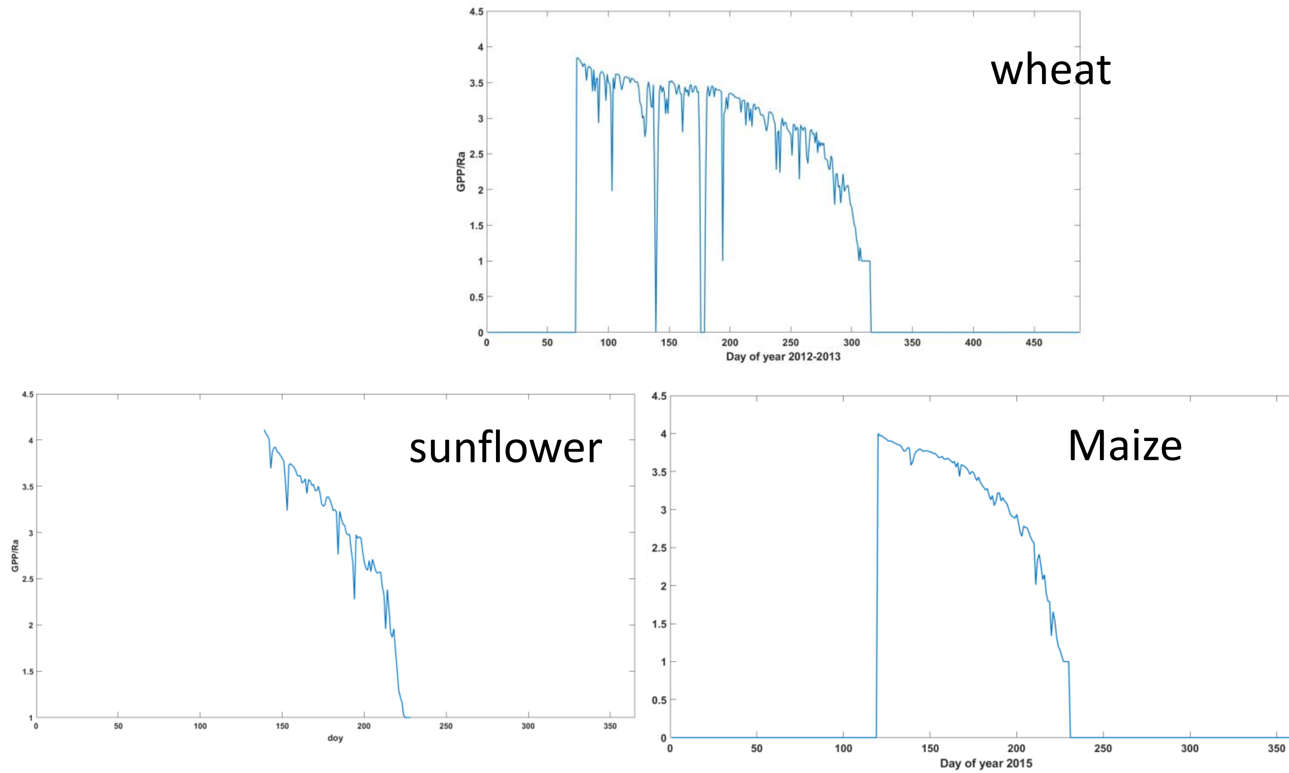
Differences in formalisms

- However…

Hoyaux et al. (2008)
Winter wheat leaves



Simulation of the ratio photosynthesis/respiration with SAFY-CO2 at stand level:



Risk of under-estimation of biomass production at the end of the season with SAFY/SAFY-WB if LUE is considered constant

Processes simulated by the model

SAFY/SAFY-WB convert solar radiation into biomass directly while SAFY-CO2/SAFYE-CO2 estimate first plant photosynthesis (GPP) and plant respiration (Ra) in order to calculate biomass.

Biomass production

$$NPP = GPP - R_a$$

Photosynthesis

$$GPP = R_g * \varepsilon_c * fAPAR * f_T(T_a) * fELUE * sR10$$

$$fELUE = ELUE_a * exp^{\left(ELUE_b * \frac{R_{df}}{R_g}\right)}$$

Plant respiration

$$R_a = R_m + R_{gr}$$

$$R_m = NPP * m_R * sR10$$

$$m_R = R_{10} * Q_{10}^{\left(\frac{T_a - 10}{10}\right)}$$

$$R_{gr} = \left(1 - Y_g\right) * (GPP - R_m)$$

Soil respiration

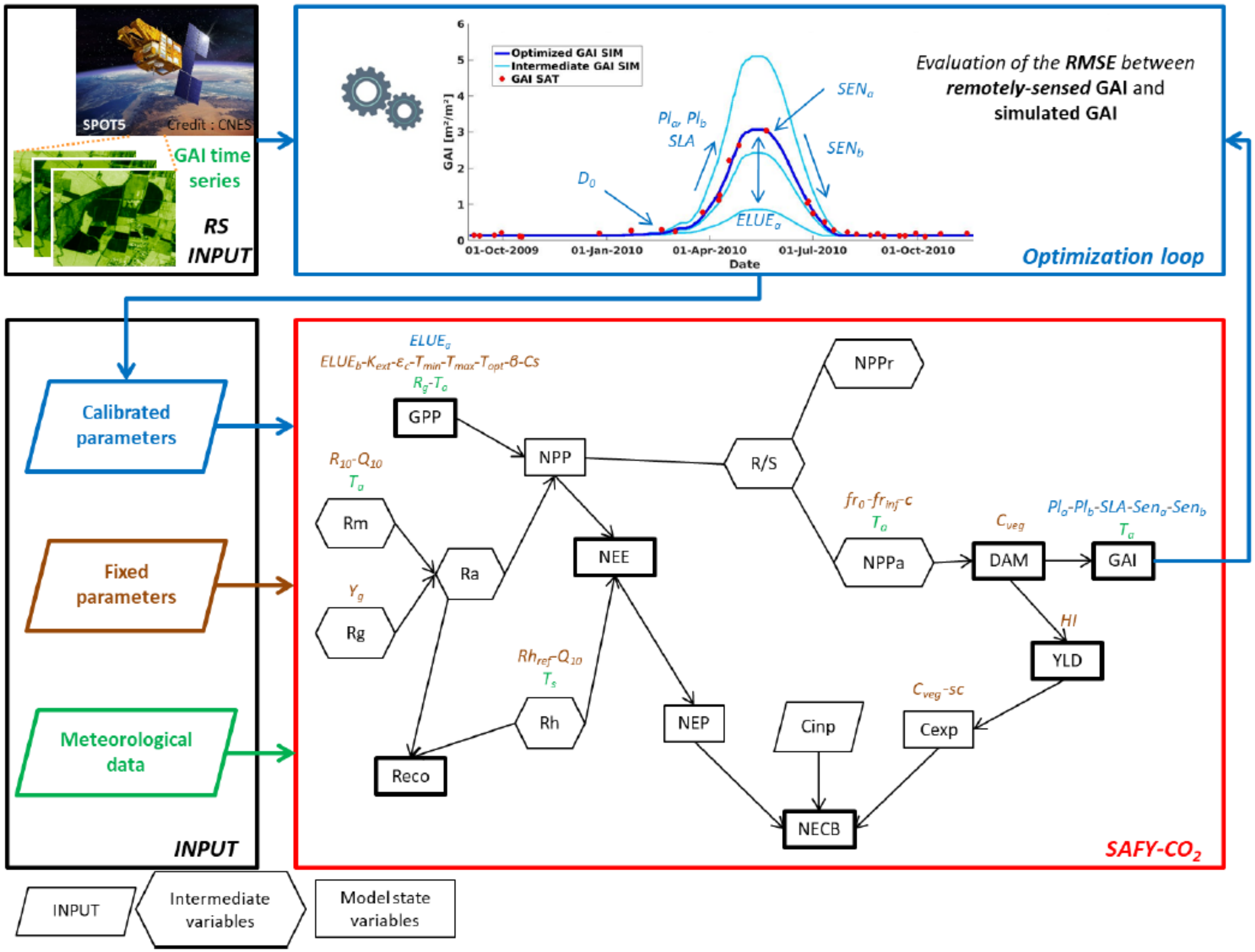
$$R_h = a * exp^{b * T_s}$$

By choice a very simple approach

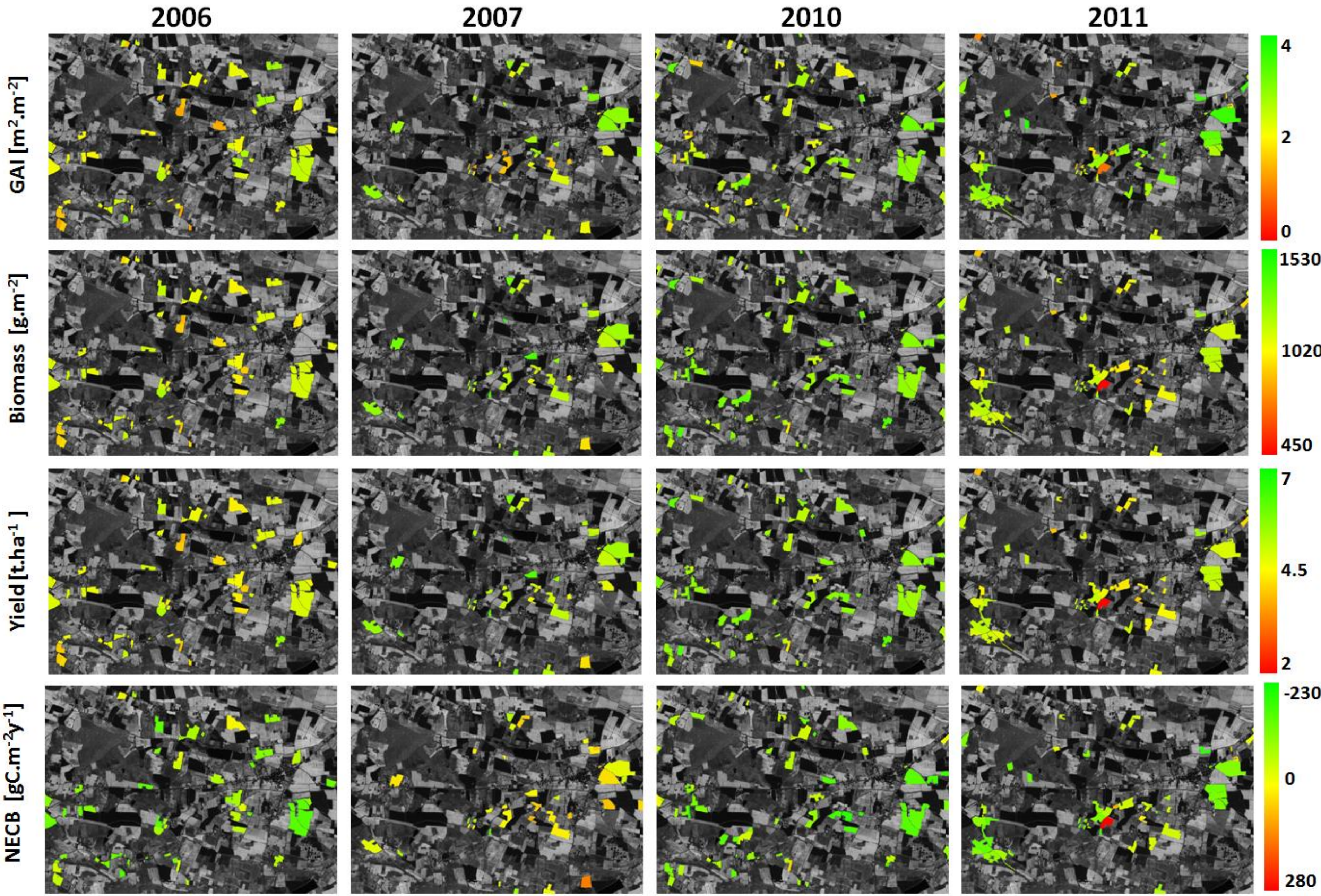
Parameters for estimating plant & soil respiration are taken from the literature

Processes simulated by the model

SAFY-CO2/SAFYE-CO2 can run without assimilating LAI time series but results won't be accurate: need to calibrate the efficiency to convert the absorbed solar radiation into photosynthesis and the phenological parameters

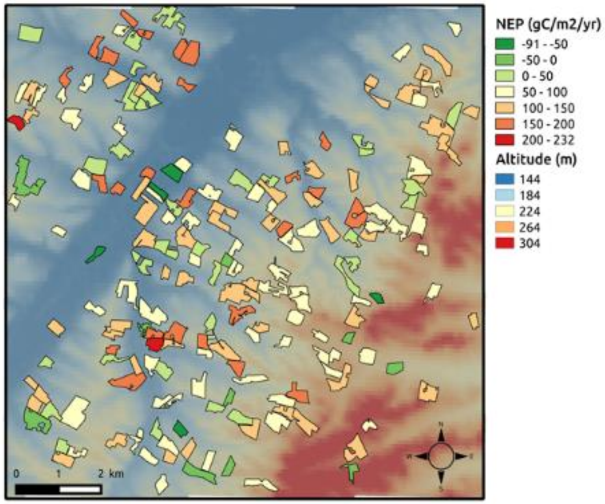


Plot scale regional estimates for winter wheat

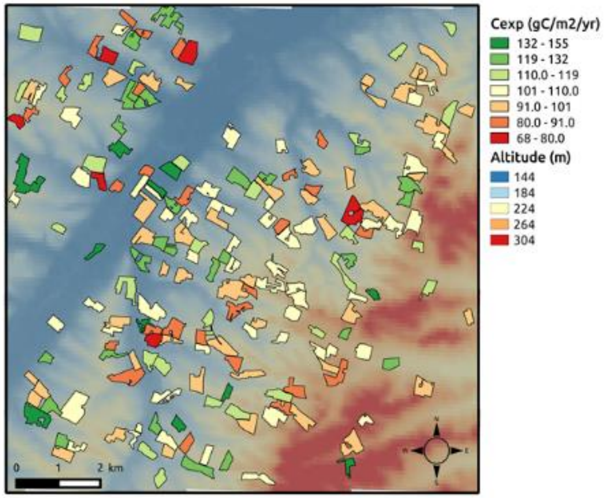


Plot scale regional estimates for Sunflower

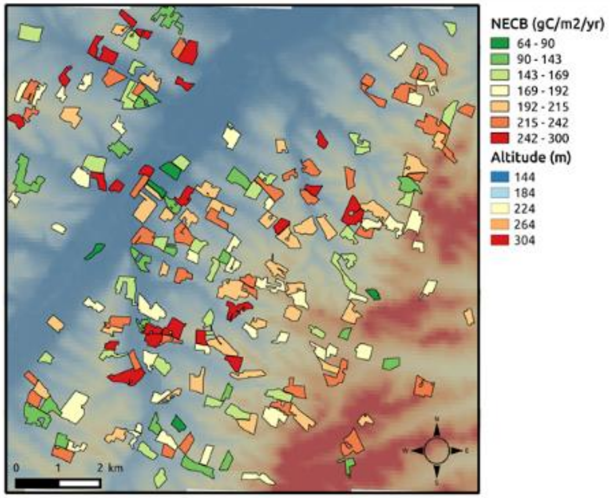
Pique et al (2020b) in Remote Sensing



Net CO_2 flux



C harvested



C budget

Plot scale simulations :

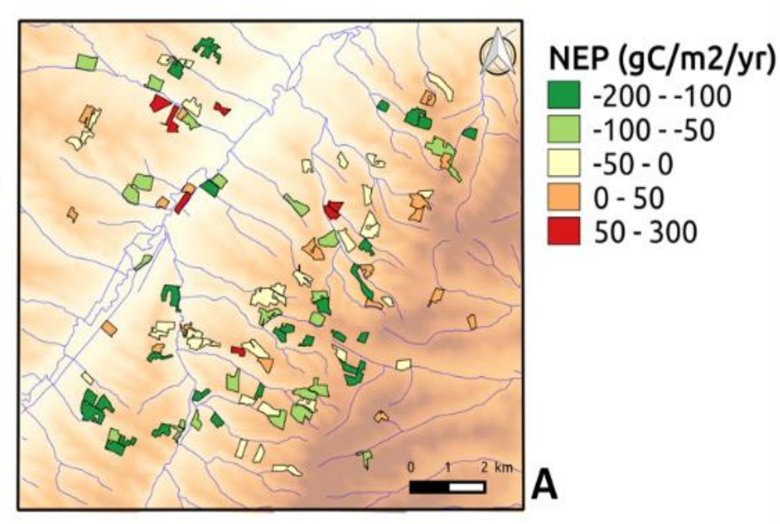
- Analysis of spatio-temporal variability of the components of the carbon budget components
- Identify the effect of some practices on the C budget

Simulation for wheat/sunflower rotation

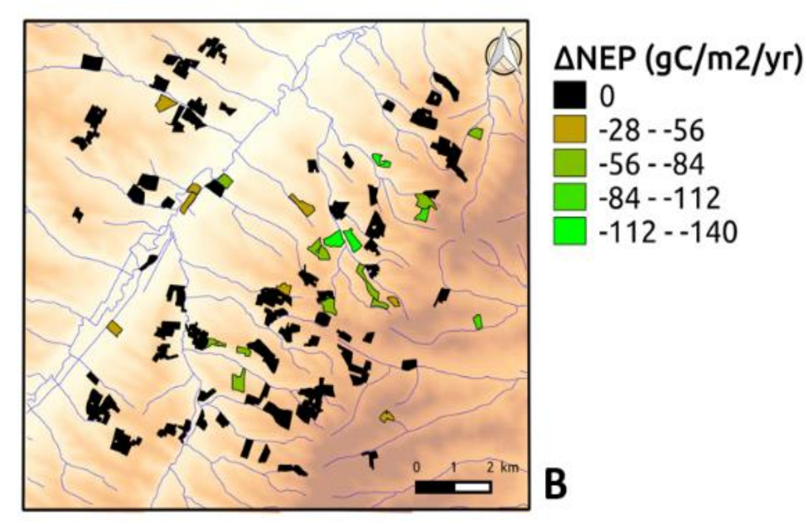
- Analysis of the effect of cover crop/spontaneous regrowth or weeds on net annual fluxes of CO_2

Pique et al (2020b) in Remote Sensing

Save & Auradé catchments



Without accounting for summer cover crops / spontaneous regrowth



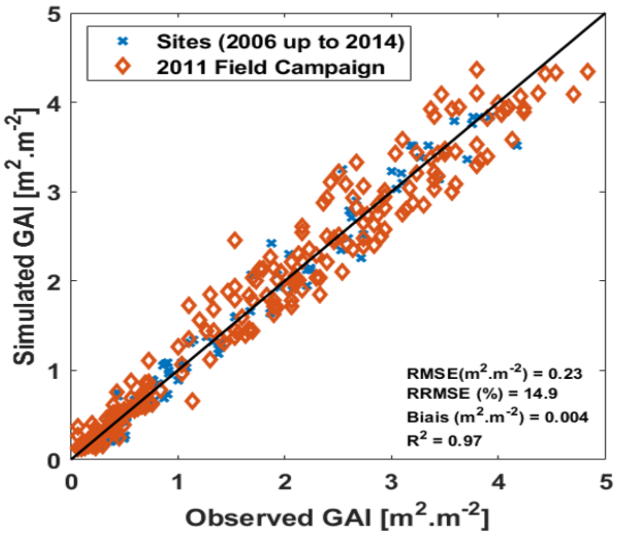
Without accounting for summer cover crops / spontaneous regrowth

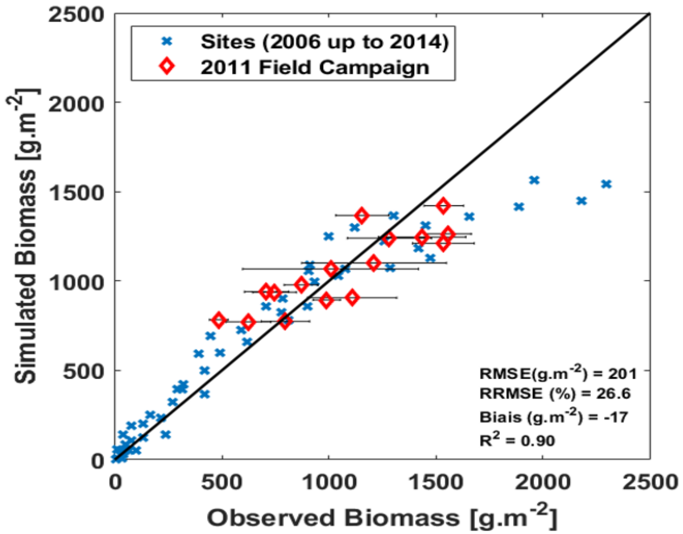
Accounting for cover crops/regrowth changes mean net annual CO_2 flux from -16.1 $gC.m^{-2}.yr^{-1}$ (bare soil fallow) to -85.2 $gC.m^{-2}.yr^{-1}$ over plots where they develop.

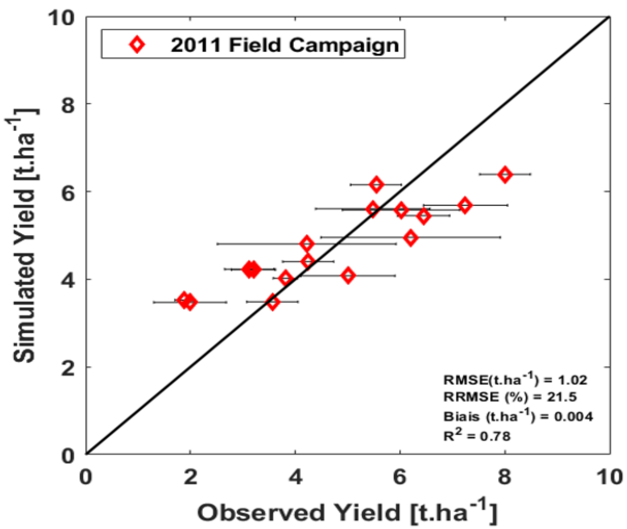
Performances of the approach

- Field campaign 2011 on winter wheat : 21 10x10m plots over 16 fields
- Good estimations of LAI & biomass

Pique et al (2020a) in GEODERMA





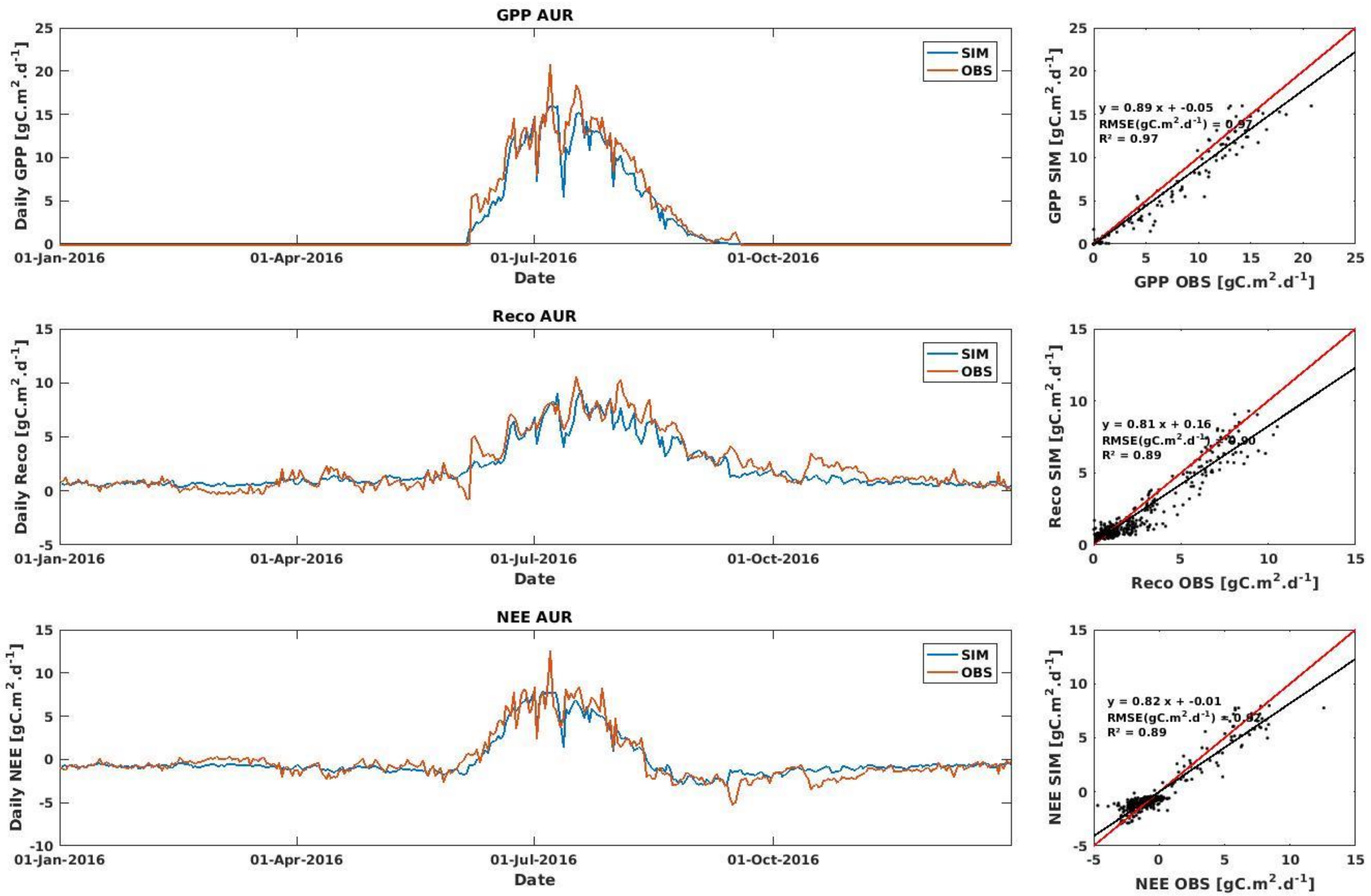


Statistics for the 2011 field campaign

	GAI	DAM	YLD
R^2	0.97	0.90	0.78
rRMSE (%)	15	27	22

Performances of the approach

CO_2 fluxes dynamics for sunflower at the Auradé site in 2016

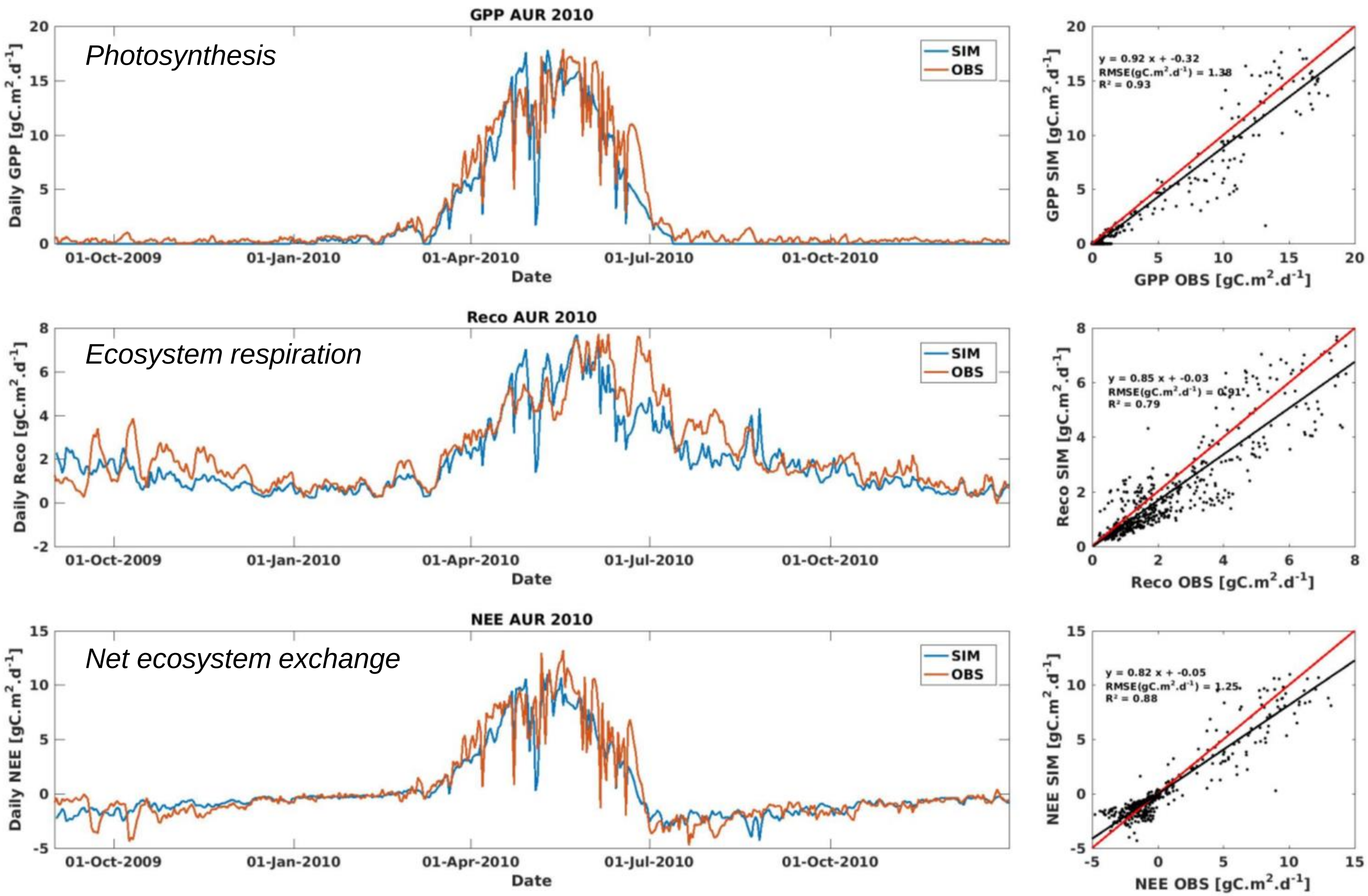


Pique et al (2020b) in Remote Sensing

Performances of the approach

Pique et al (2020a) in GEODERMA

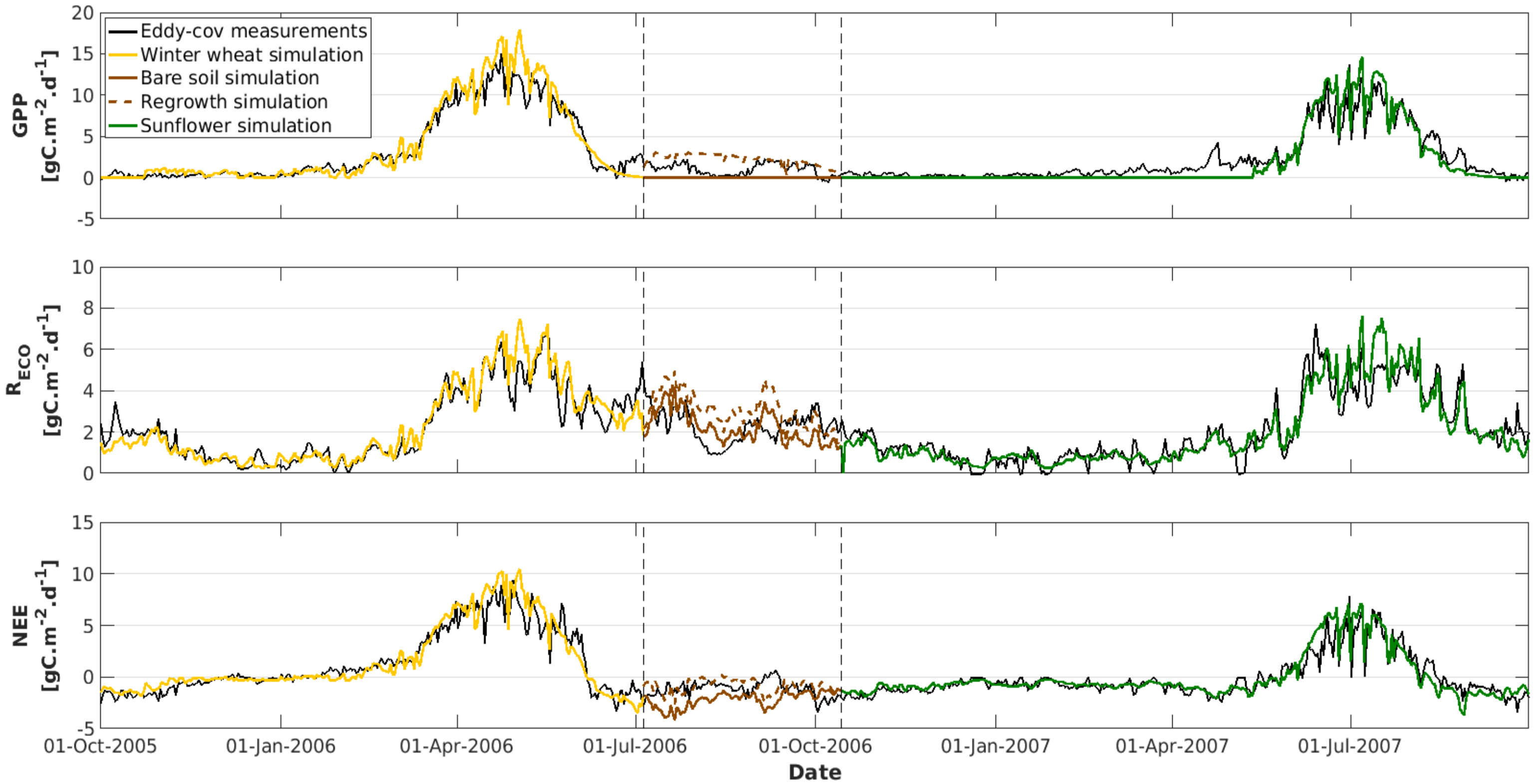
CO_2 fluxes dynamics for wheat at the Auradé site in 2010



- Very good agreement with observations
- NEE statistics for 8 cropping years of wheat : **R^2 = 0,86** ; **RMSE = 1,29gC.m^{-2}.d^{-1}**
- Possibility to compute carbon budget over cultural year

Performances of the approach

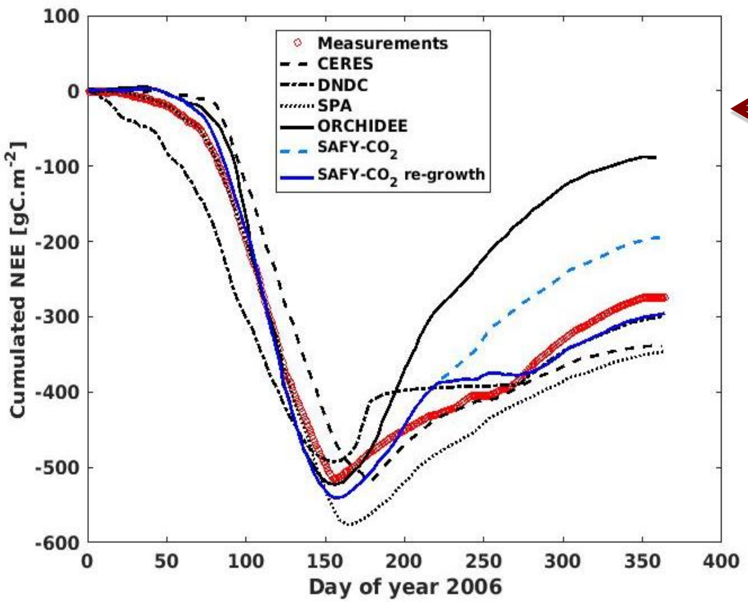
- Possibility to chain 2 years of simulations and take into account or not the effect of cover crops/regrowths/weeds in an automated way on water/C fluxes and budgets



Pique et al (2020b) in Remote Sensing

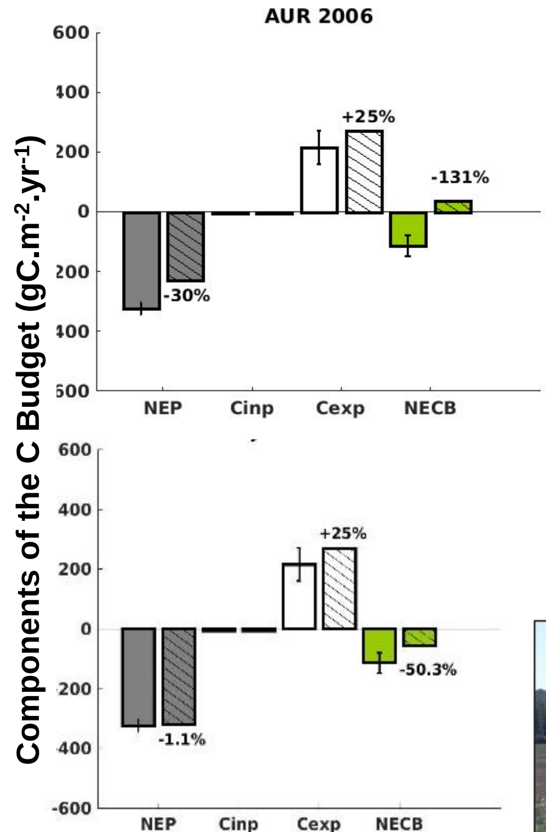
Performances/Originality of this approach

With and without accounting for regrowth events



Wattenbach et al. (2010)
Pique et al. (2020a)

Observations vs Simulations



No accounting for regrowth, cover crops or weeds

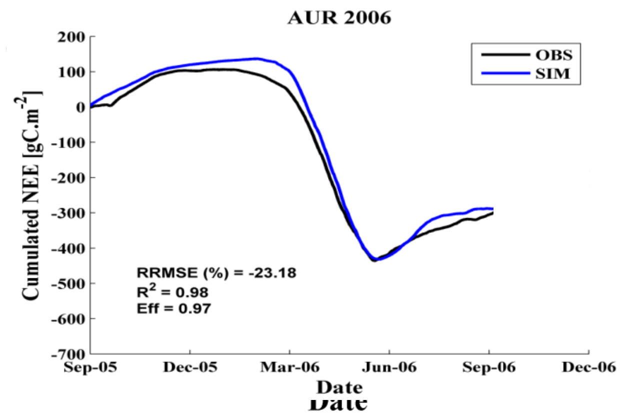
Accounting for regrowth, cover crops, weeds from remote sensing

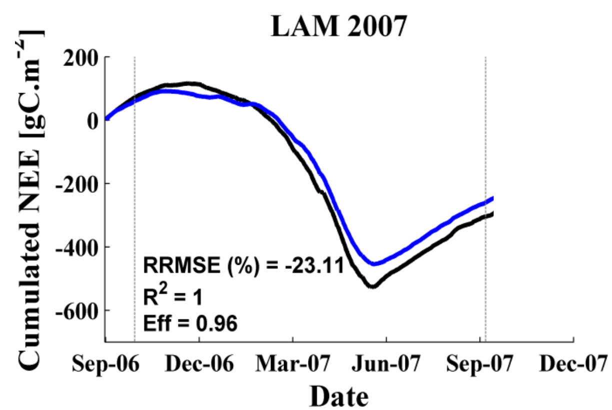
Very good performance of this simple modelling approach that requires little data on management (straw export, organic amendments..) compared to other models.

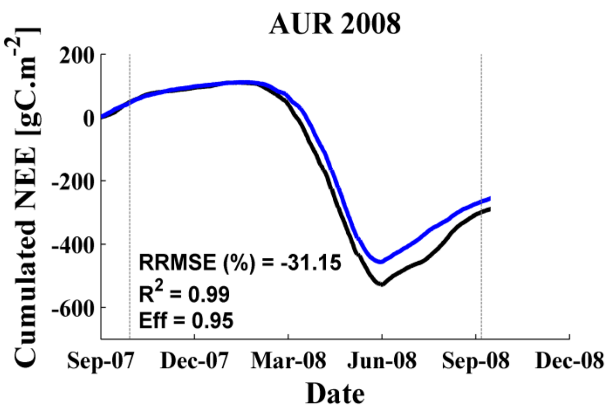
Shows the power of remote sensing for constraining this crop model

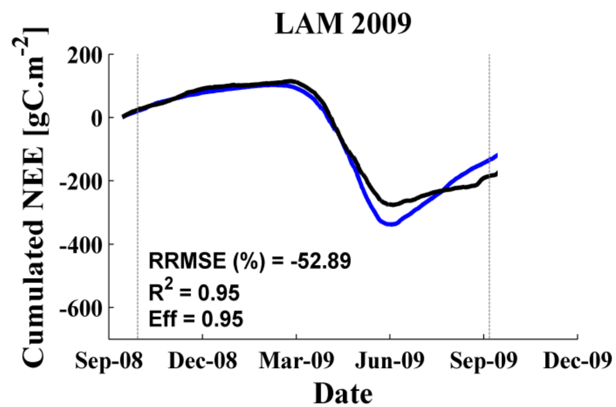
Performances of the approach

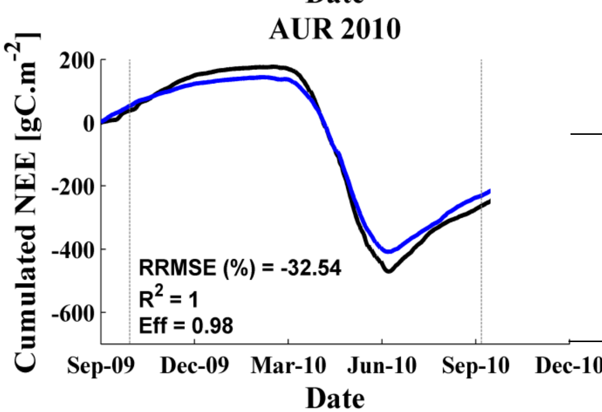
SAFYE-CO_2









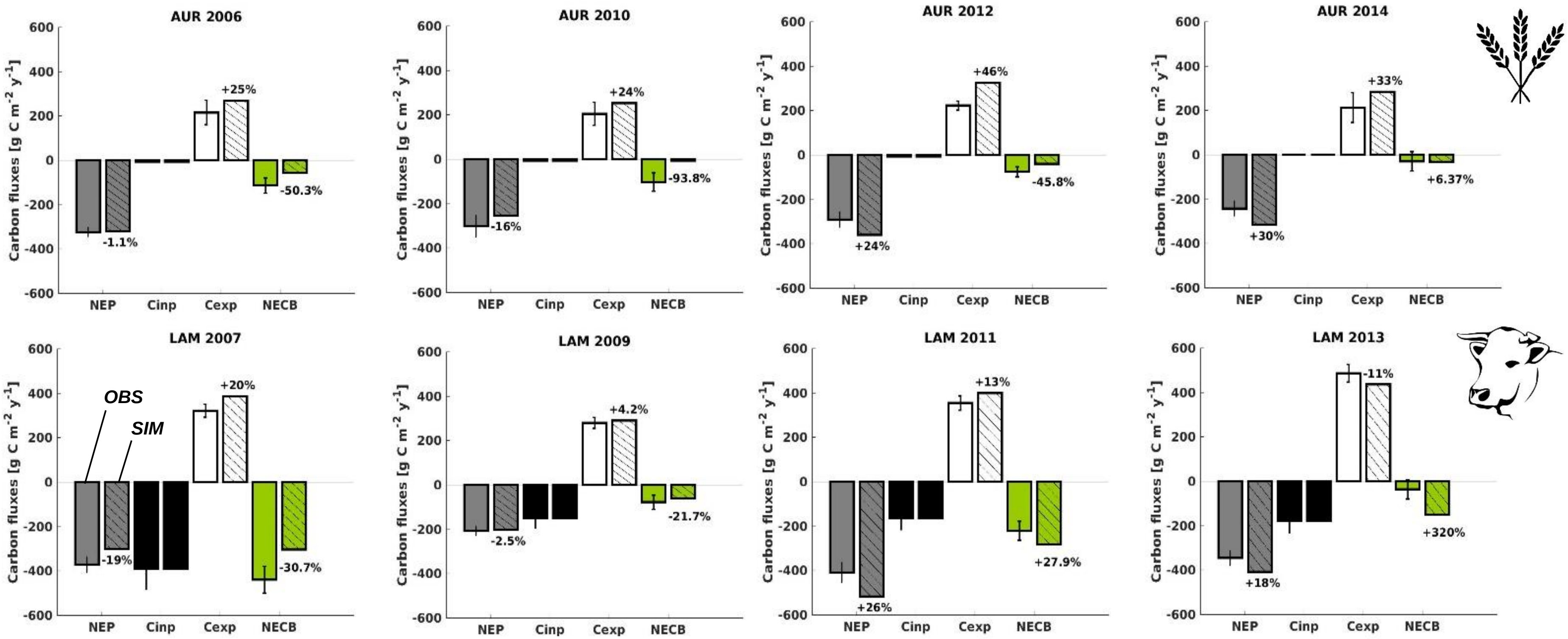


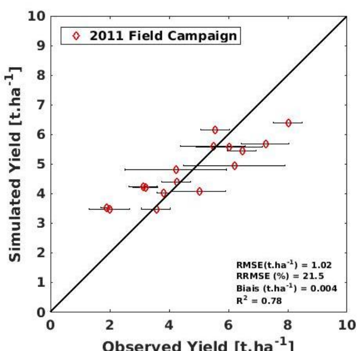
	NEE		
	R^2	RMSE*	Slope
AUR2006	0.85	1.21	1.02
LAM2007	0.87	1.06	0.81
AUR2008	0.89	1.05	0.87
LAM2009	0.79	1.19	0.88
AUR2010	0.88	1.28	0.79

Performances of the approach

Annual carbon budget over 8 winter wheat cropping years
Lamasquère & Auradé sites

SAFYE-CO_2



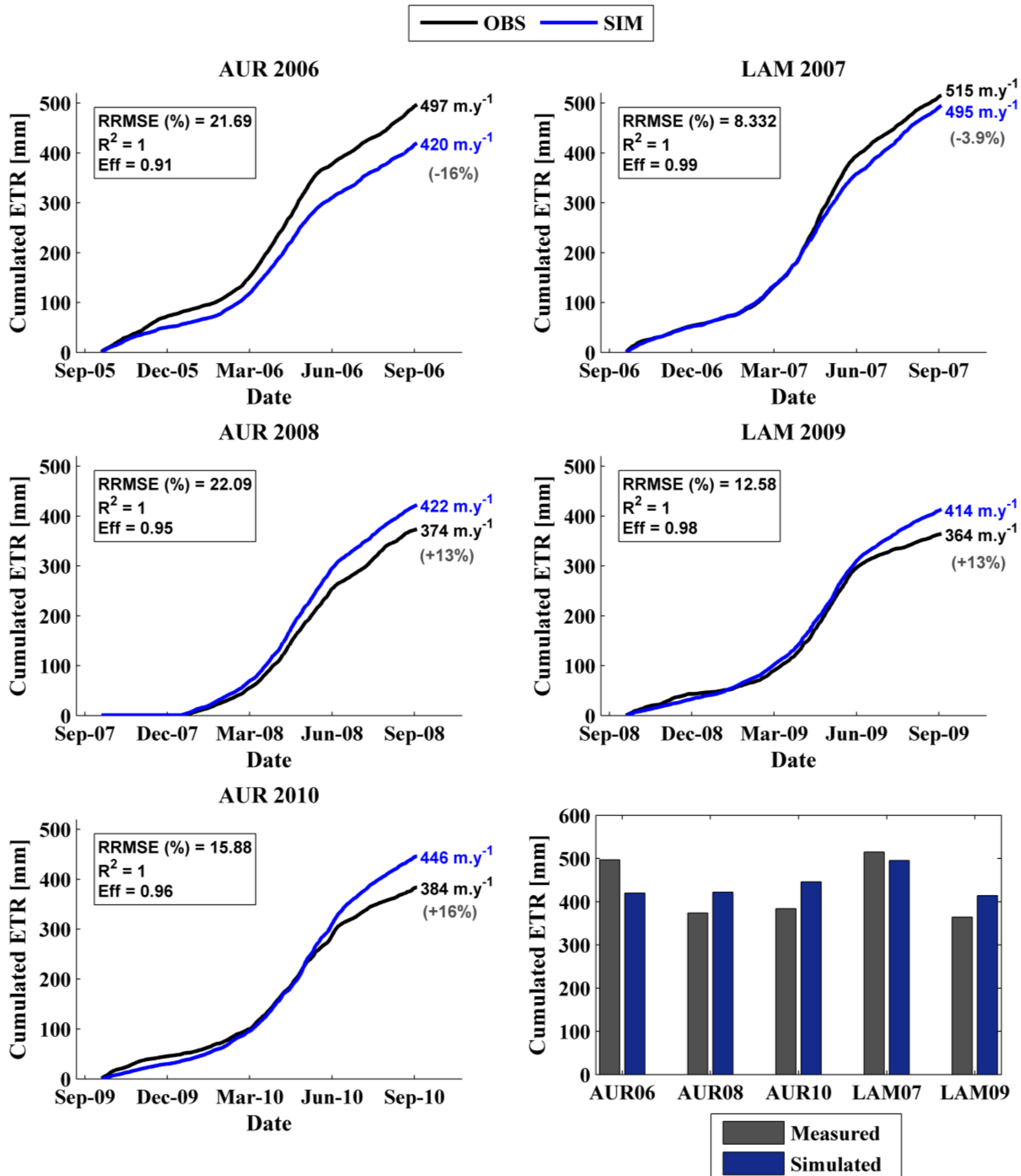


- ΔCarbon budget ϵ [**1,8 ; 134,8**] gC.m^{-2}.yr^{-1}
- Uncertainties on in situ Cexp
- Estimation of soil C variation

Performances of the approach

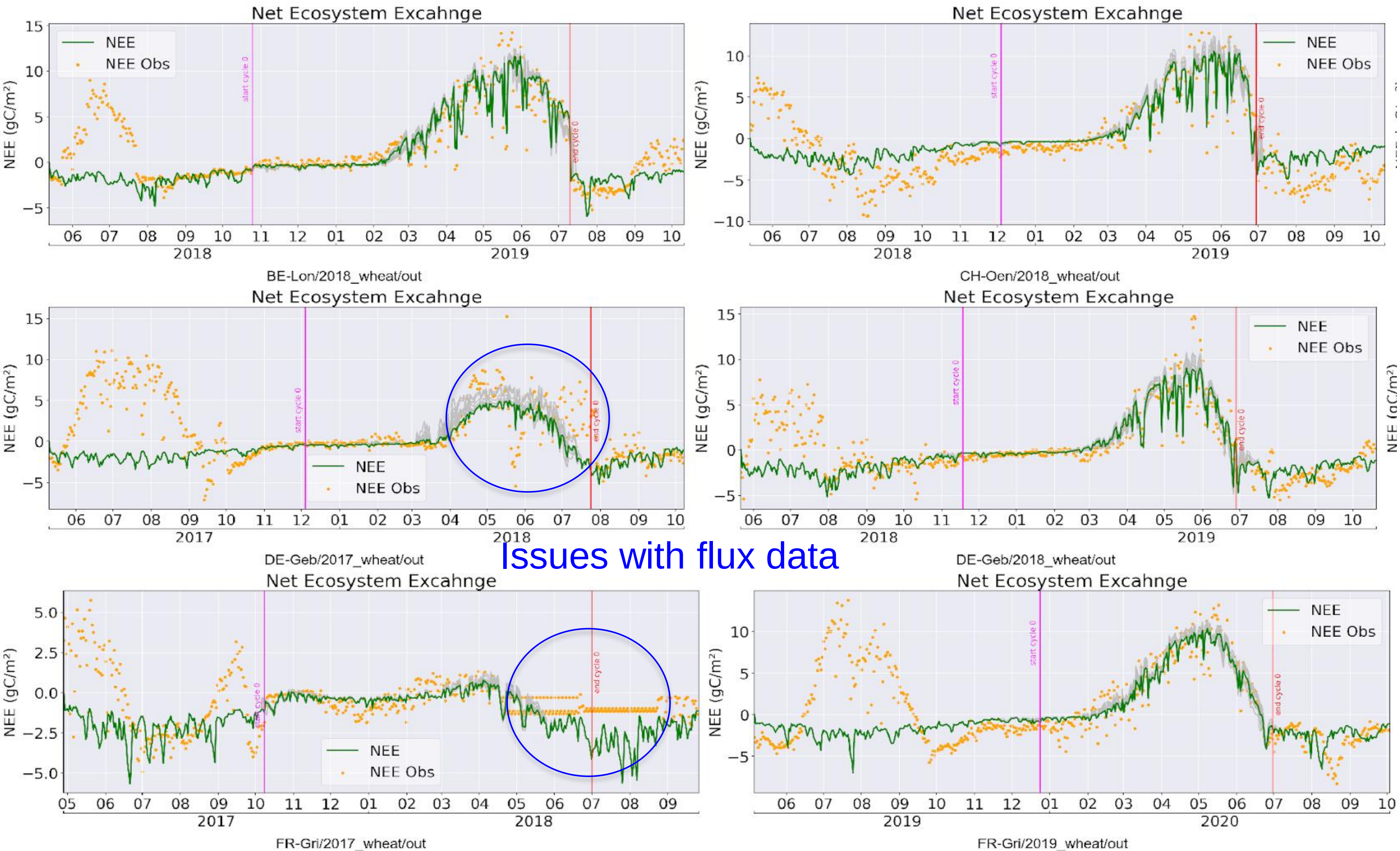
cumulated ETR

SAFYE-CO_2



Transposability of the approach

European flux sites Europe for winter wheat (no change in original parameters) ➔ LAI derived from Google Earth Engine



Realisation T. Wijmer & A. Al Bitar

Limits of the approach

- Diagnostic approach but some scenarii can be tested (e.g. straw exported or not),
- Calibration procedure based on a Simplex approach does not allow simulations over more than a couple of thousand plots for a given run ➔ otherwise AgriCarbon-EO tool,
- Optical RS data : problem for calibrating when long cloud coverage and LAI saturates for high biomass); ➔ Sentinel 1,
- Need for farmer's data on straw/biomass export and organic amendments for calculation of the C budget,
- Only annual C budgets can be estimated with the simple formalisms for soil respiration and no accounting for priming effect ➔ coupling with soil model (e.g. AMG) for pluri-annual assessment of C budget and compliance with international standards (e.g. Verra) for monitoring C stocks ➔ AgriCarbon-EO

The AgriCarbon-EO processing chain

An end to end processing chain adapted to large scale applications & high resolution: parallelized bayesian inversion approach ➔ uncertainty analysis, super computers… see Al Bitar, Wijmer et al. submitted to https://egusphere.copernicus.org/preprints/2023/egusphere-2023-48/

ACEO

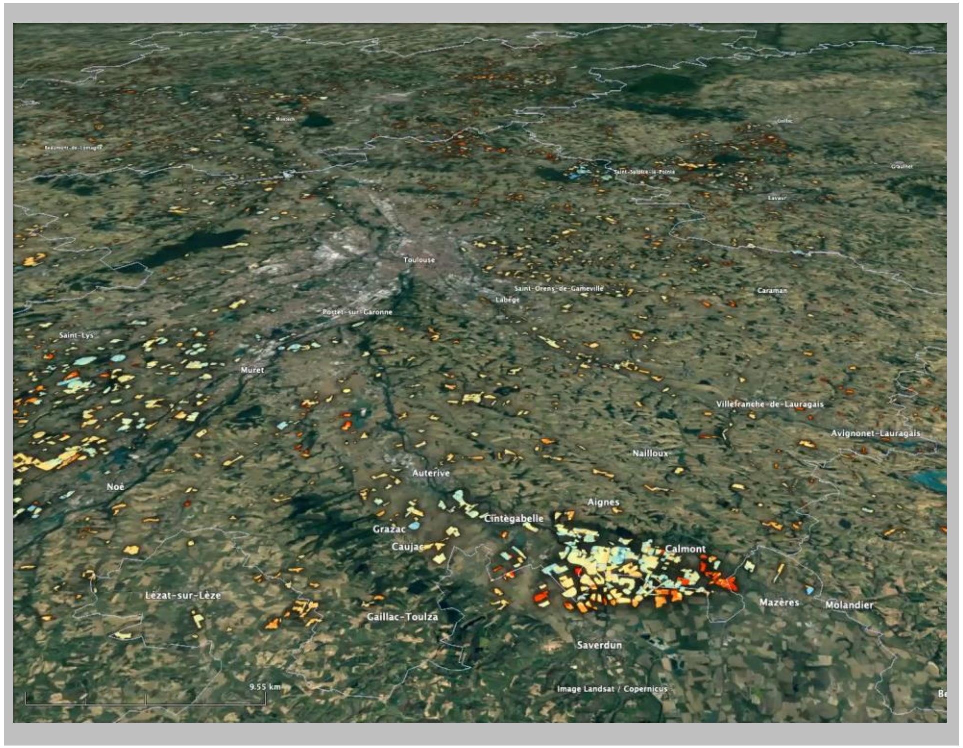
BASALT

Bayesian Normalised Importance Sampling using Look-out Table

SAFYE-CO2

Parsimonious multicycle crop model for carbon and water budget

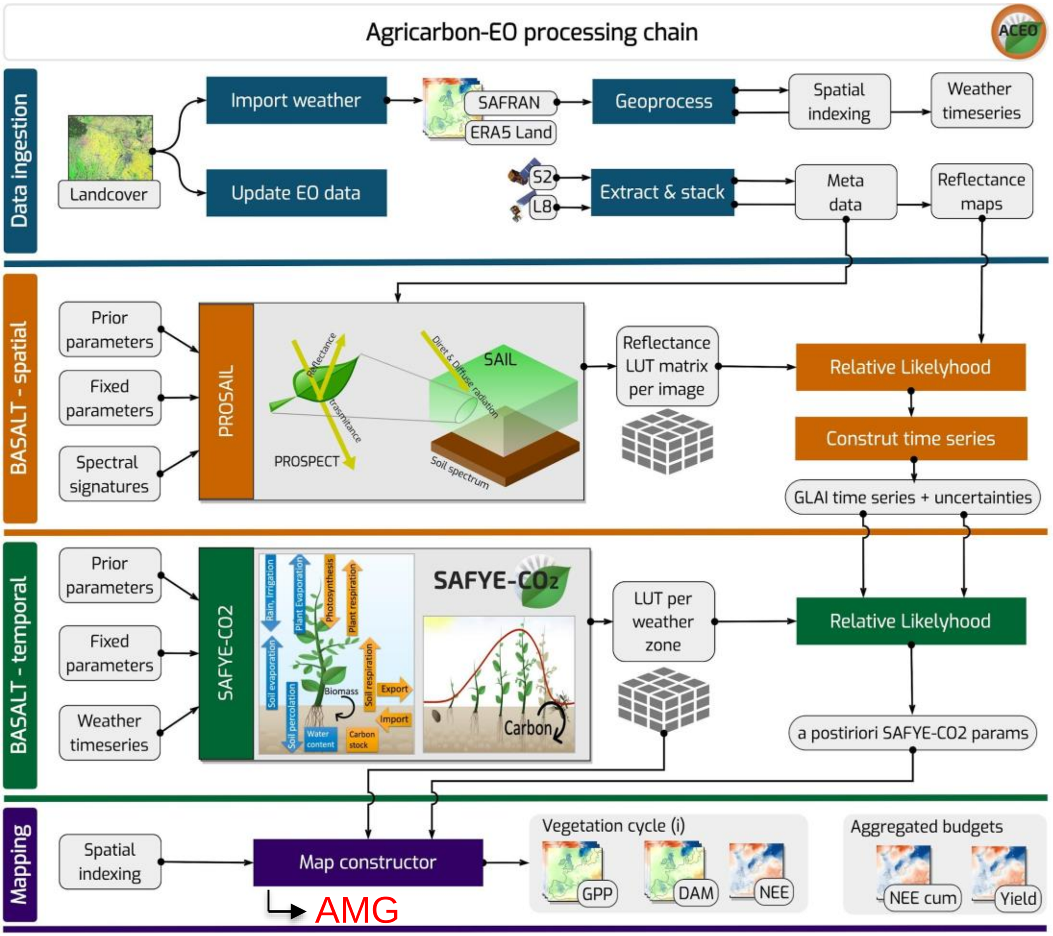
Example output:
Net Ecosystem Exchange over Wheat for 110x110 km at 10m (in France)



A scalable solution for carbon budget monitoring compliant with recommendations by the CIRCASA initiative (Smith et al. 2020) and the voluntary C market standards

The AgriCarbon-EO processing chain

An end to end processing chain adapted to large scale applications & high resolution: parallelized bayesian inversion approach ➔ uncertainty analysis, super computers… see
Al Bitar, Wijmer et al. submitted to https://egusphere.copernicus.org/preprints/2023/egusphere-2023-48/



Downloads, colocates and regrids data from optical satellites (Sentinel 2, Landsat 8), weather reanalysis ERA5LAND (ECMWF)/SAFRAN (Meteo France) & validation data

Bayesian LUT based Inversion of **Prosail** for each image to obtain **LAI +uncertainties**

Bayesian LUT based assimilation of LAI time series into **SAFYE-CO2** to obtain **parameters and variables**

Produces

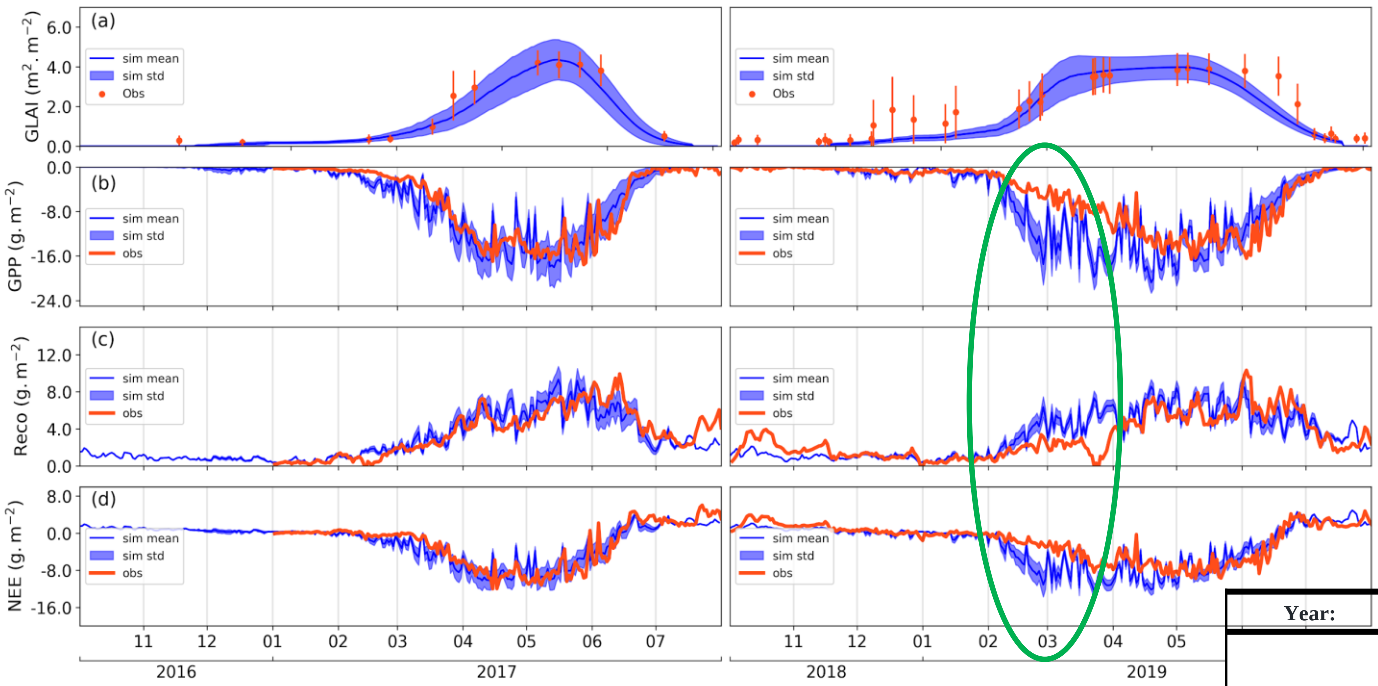
- Quality indicators & uncertainties
- Maps of variable & parameter as well as their distributions.

SAFYE-CO2 simulation over one Sentinel2 tile 4h

For more details see : https://www.cesbio.cnrs.fr/agricarboneo/agricarbon-eo/

Validation of the CO_2 fluxes (GPP, Reco, NEE)

PhD T. Wijmer



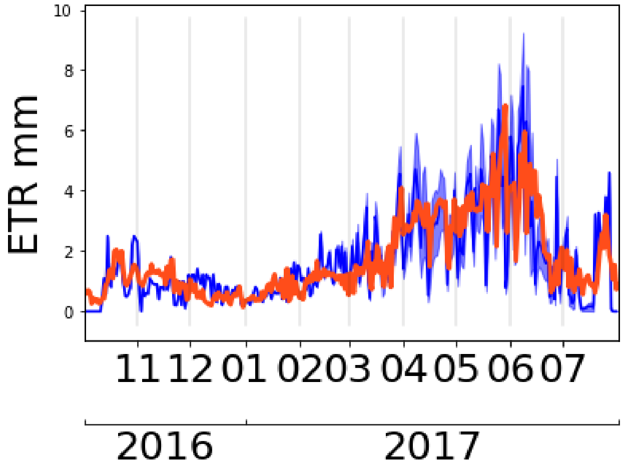
Gapfilled in-situ data

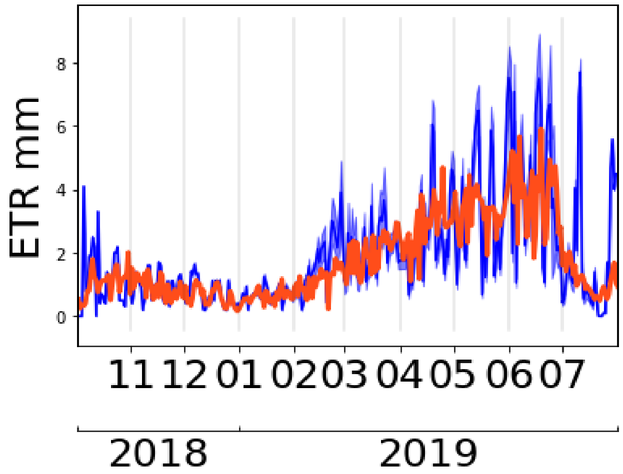
- **Good performances Overall**

Year:	stats	2017	2019
GLAI	Bias (m2.m-2)	0.26	0.35
	R2	0.93	0.88
	RMSE (g.m-2)	0.48	0.64
GPP	Bias (g.m-2)	0.36	1.23
	R2	0.91	0.76
	RMSE (g.m-2)	1.91	3.43
Reco	Bias (g.m-2)	0.03	-0.33
	R2	0.62	0.60
	RMSE (g.m-2)	1.91	1.59
NEE	Bias (g.m-2)	0.38	0.89
	R2	0.88	0.88
	RMSE (g.m-2)	1.69	2.40

Validation of the water fluxes (ETR, SWC)

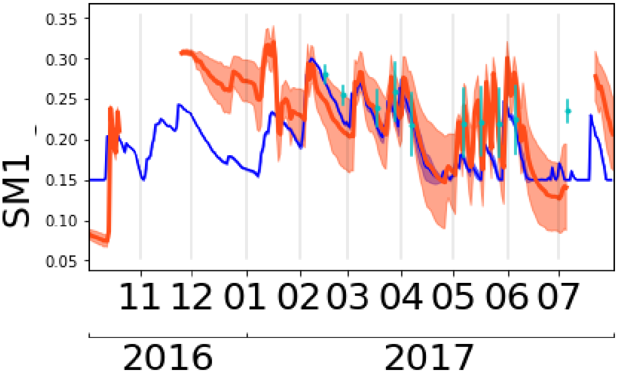
PhD T. Wiimer

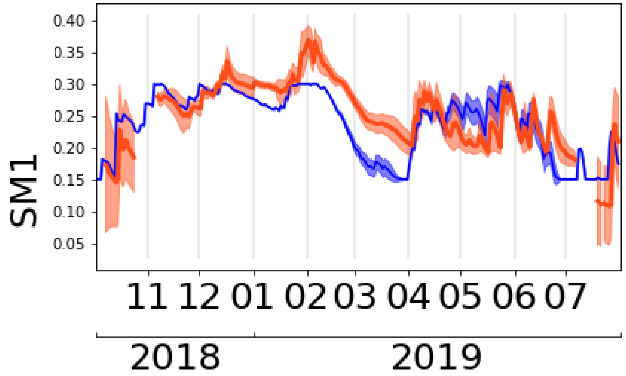




Simulations

Observations at Auradé

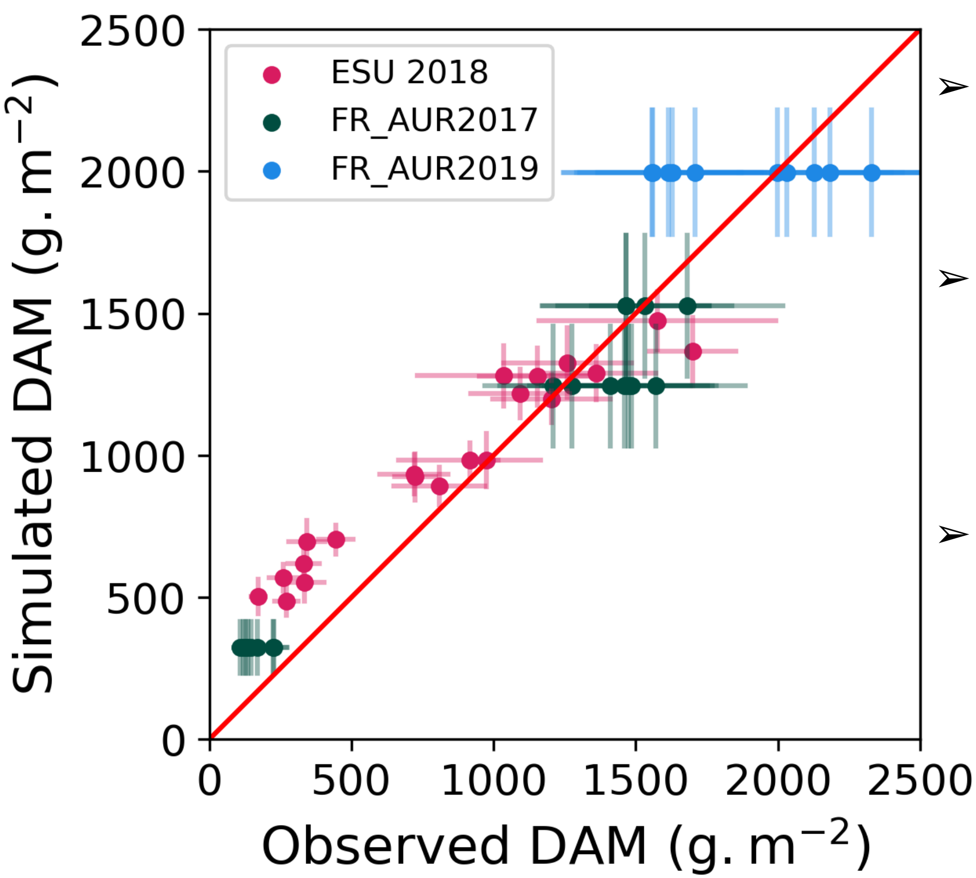




- ➢ **ETR & SWC simulations ok both years**

Validation of aboveground biomass

Realisation T. Wijmer



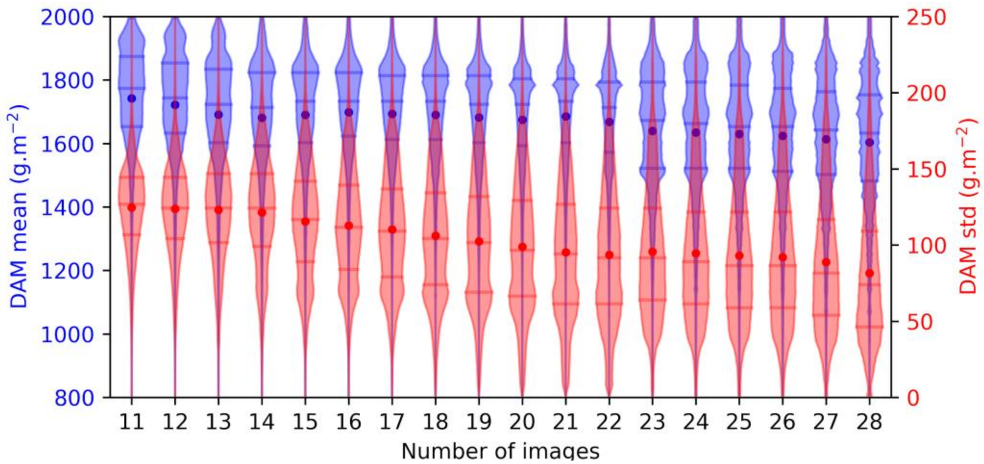
- Slight overestimation of early-cycle biomass
- Saturation effect for very strong biomass (the biggest ever observed in the area)
- Strong correlation and low dispersion knowing model uncertainties and observation

DAM obs.	RMSE	MAE	Bias	R2
ESU-2018	211.34	180.89	-129.44	0.94
FR-AUR-2017	172.34	150.83	-6.46	0.97
FR-AUR-2019	380.62	323.96	4.78	-
All	250.34	203.35	-52.04	0.90

measurements collected in 2017 and 2019 at Auradé, and in 2018 as part of the Sensagri & Bag'gages projects

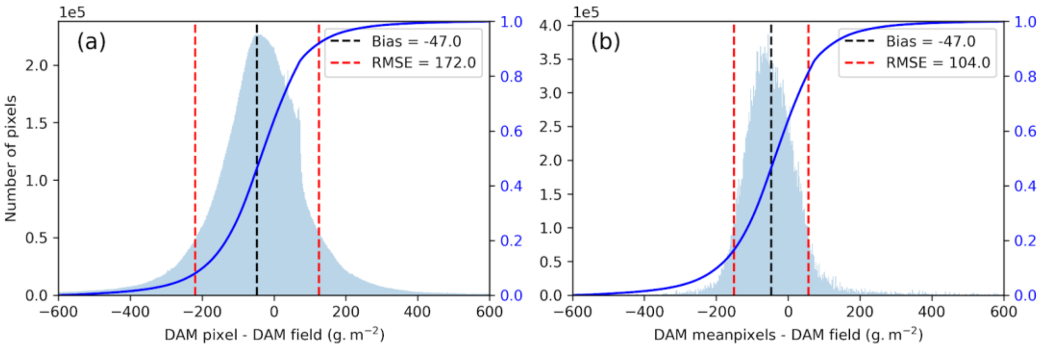
Number of images and agregation of the results

Effects of the number of images on simulated biomass



- More of images reduces uncertainty on biomass
- But has little effect on the average biomass

Effects of simulation resolution on simulated biomass

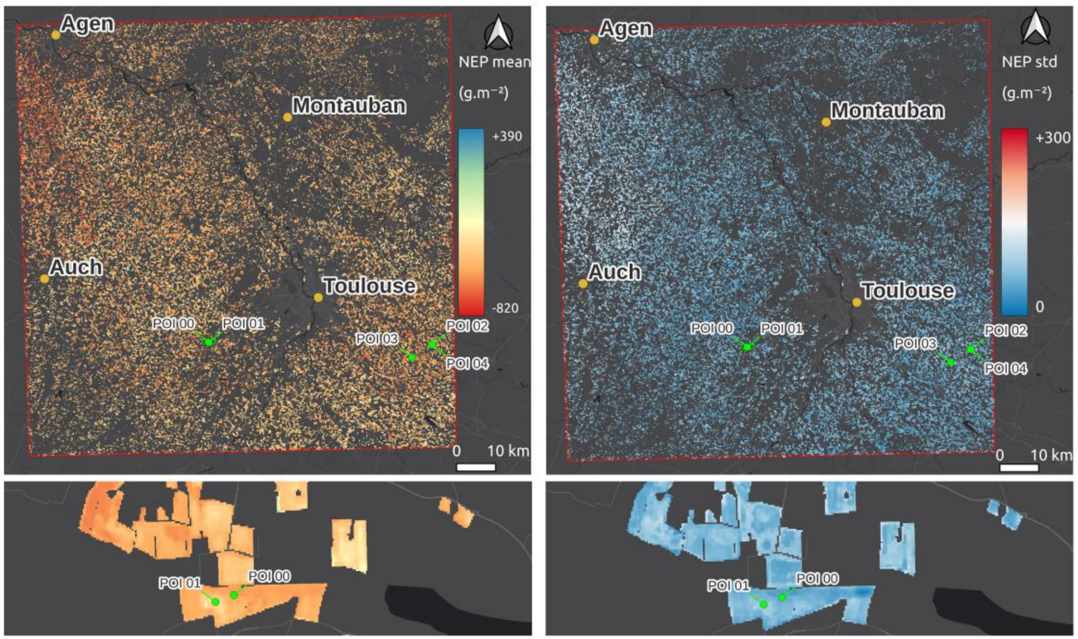


- Difference between pixel and plot analysis because of intra plot variability
- Difference between the results from the pixels aggregated at plot level and the simulations at the plot (non linear effects)

AgriCarbon-EO’s output

PhD T. Wijmer co- financed by H2020 NIVA & Naturellement Popcorn

Net annual CO_2 gluxes (in gC-CO_2.m^{-2}.yr^{-1}) at 10m resolution for straw cerals in 2017 (left) & associated uncertainties (right)



Area of 110x110 km near Toulouse (Tile 31 TCJ)

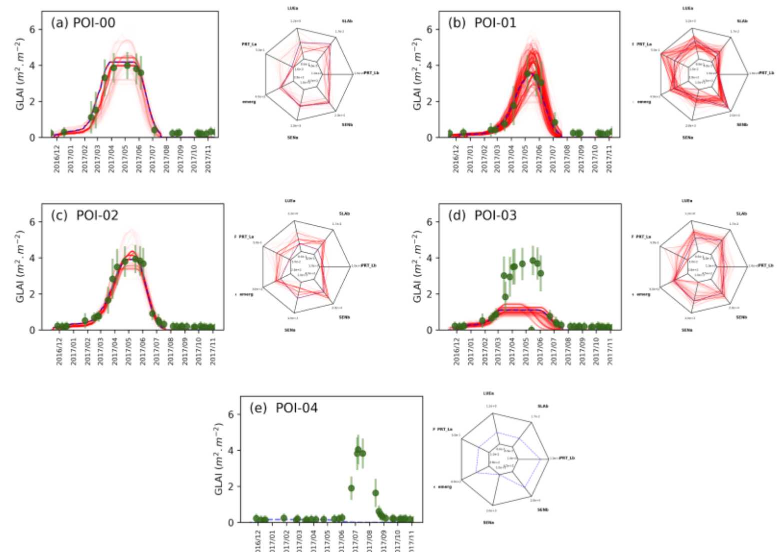


Illustration of the simulations for 5 Points Of Interest :

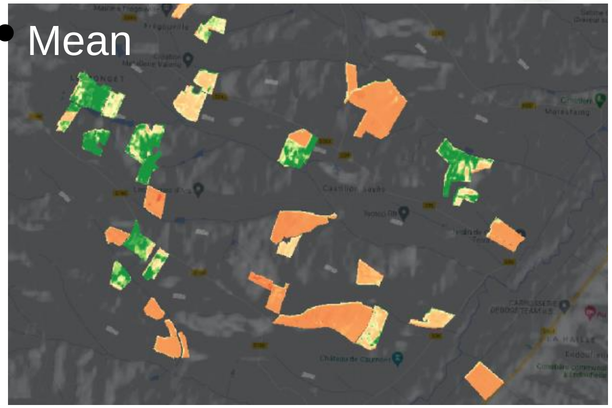
- **a & b - pixels in the same plot**
- **c & d - non filtred cloud**
- **e – wrong declaration of the farmer (summer crop, not wheat)**

AgriCarbon-EO’s output

Mapping crop and cover crop biomass at 10m resolution

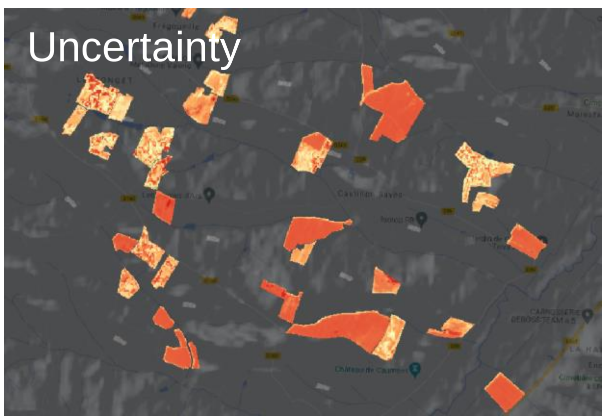
Fava bean

Low biomass and very heterogeneous



g C of dry mass/m²: 0, 150, 300, 450, 600

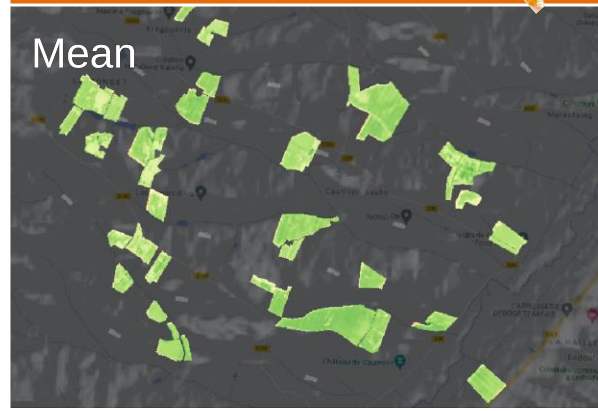
Rather high relative uncertainty



g C of dry mass/m²: 0, 75, 150, 225

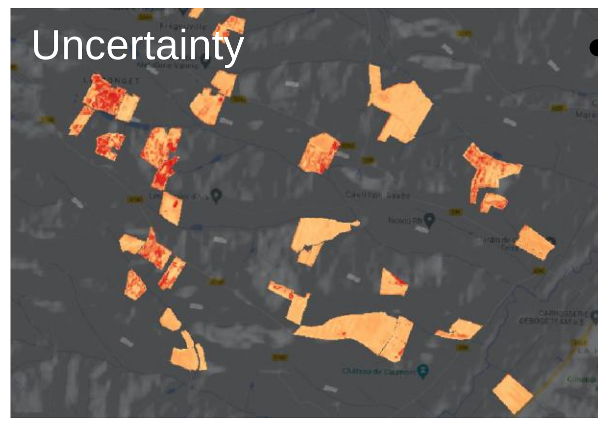
Popcorn maize

Typical and fairly homogeneous high biomasses



g C of dry mass/m²: 0, 625, 1250, 1875, 2500

Variable uncertainty within plots but less than for cover crops

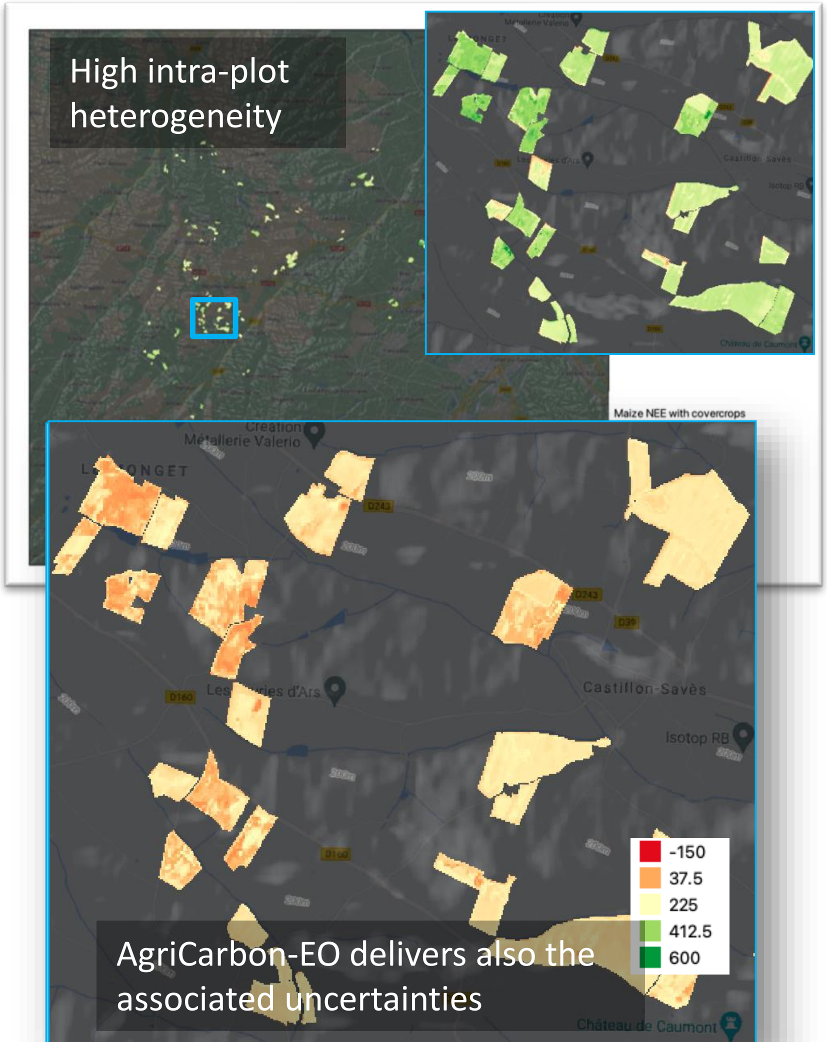


g C of dry mass/m²: 0, 250, 500, 750, 1000

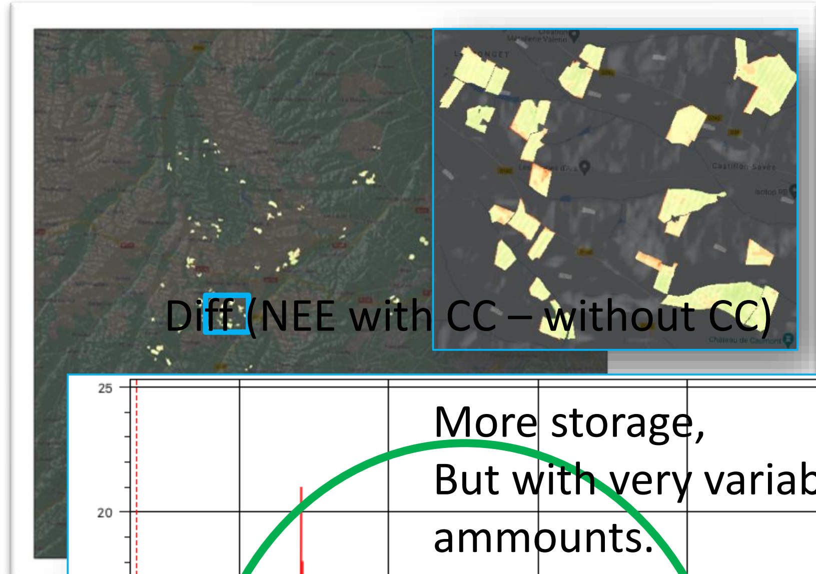
Realisation A. Al Bitar

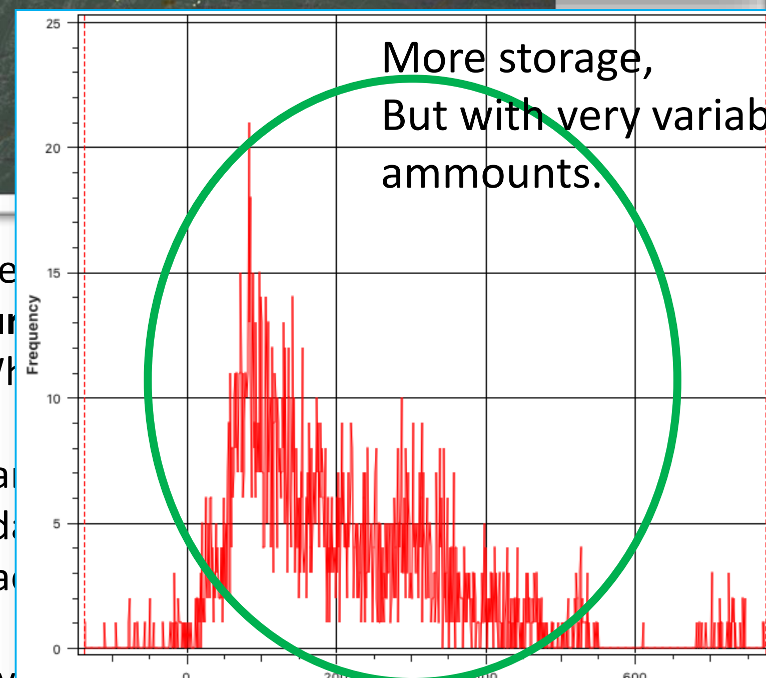
Effect of cover crops on CO_2 fluxes

NEE with covercrops



NEE without covercrops





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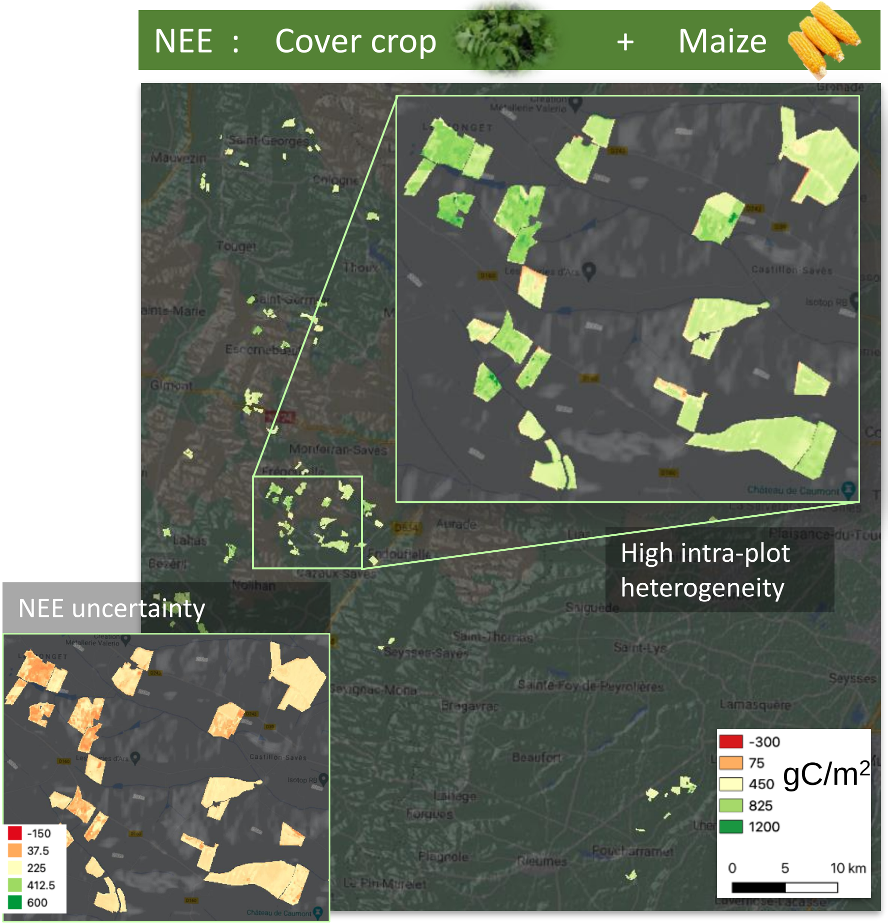
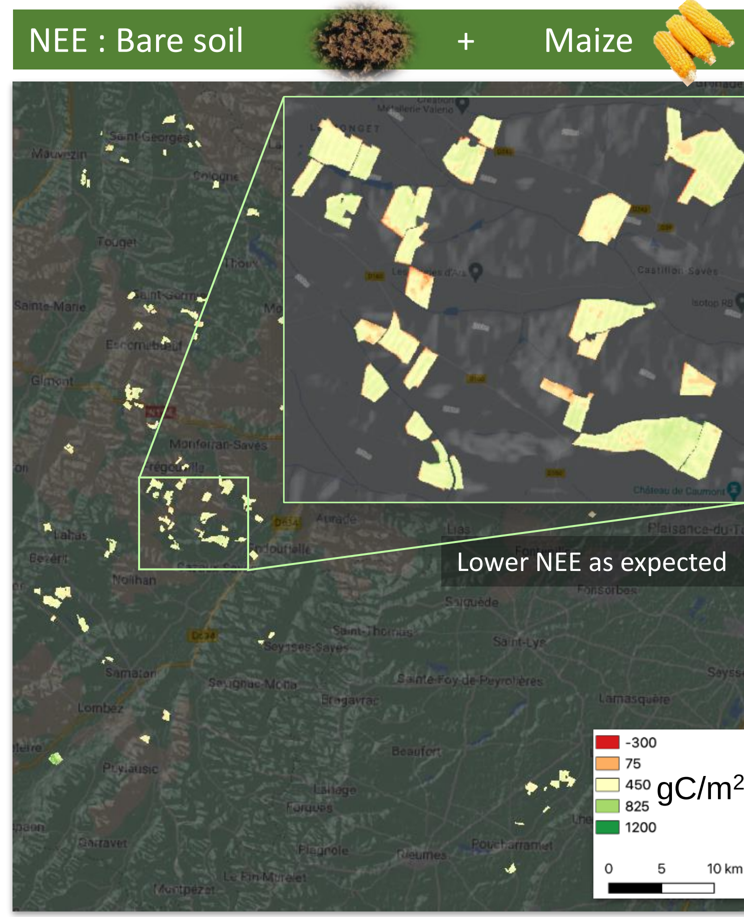
Our ...
-Wh ... ?

-Ca ... el-1
rad...
pra... .

- Ev... ld data

Effect of cover crops on CO_2 fluxes

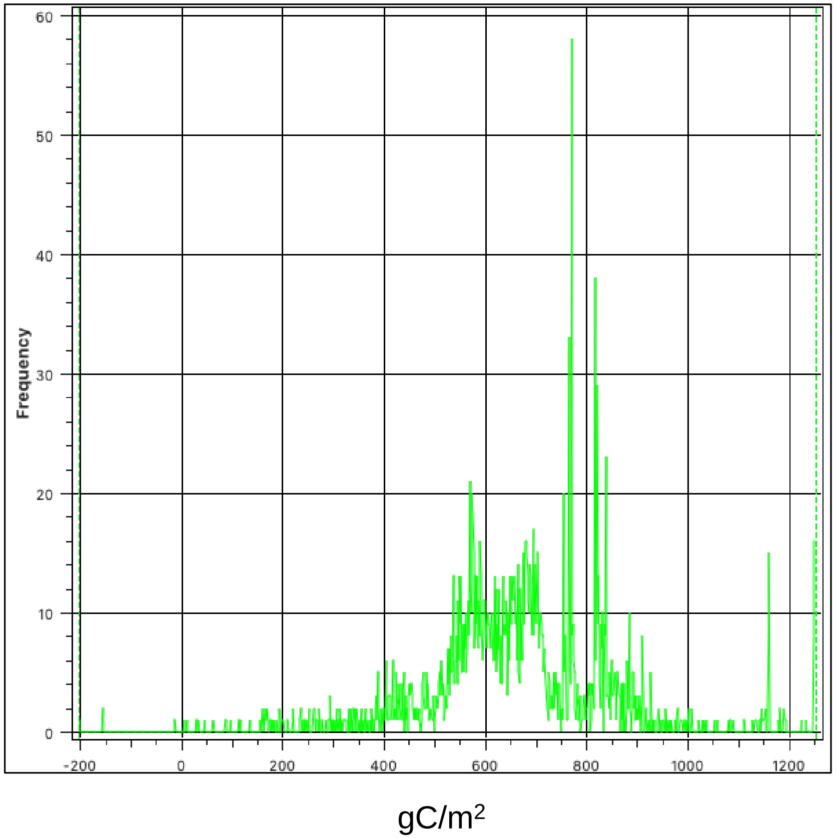




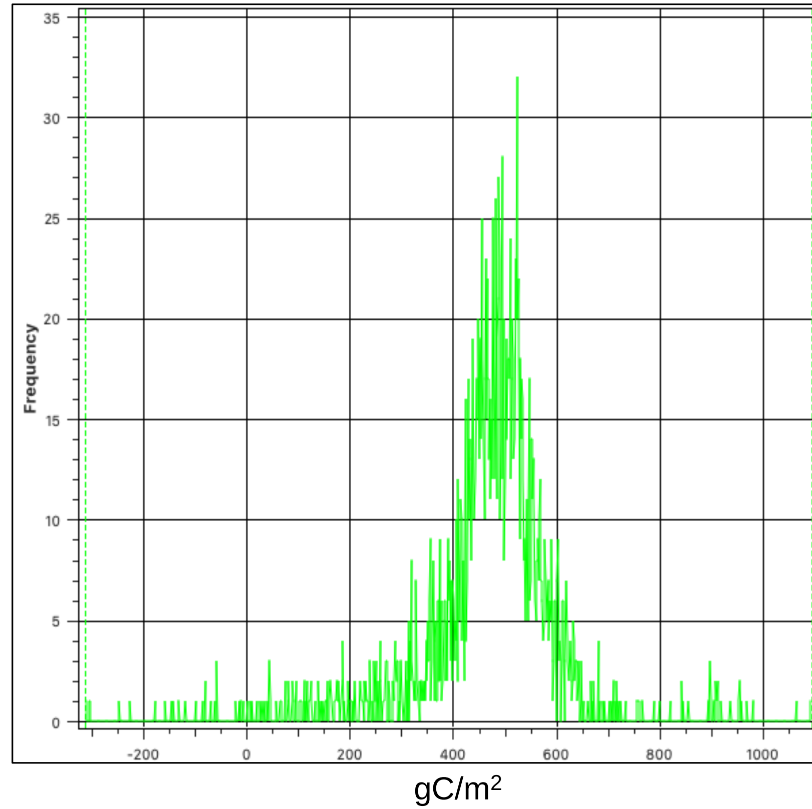
Realisation A. Al Bitar

Effect of cover crops on CO_2 fluxes

NEE : Cover crop + Maize



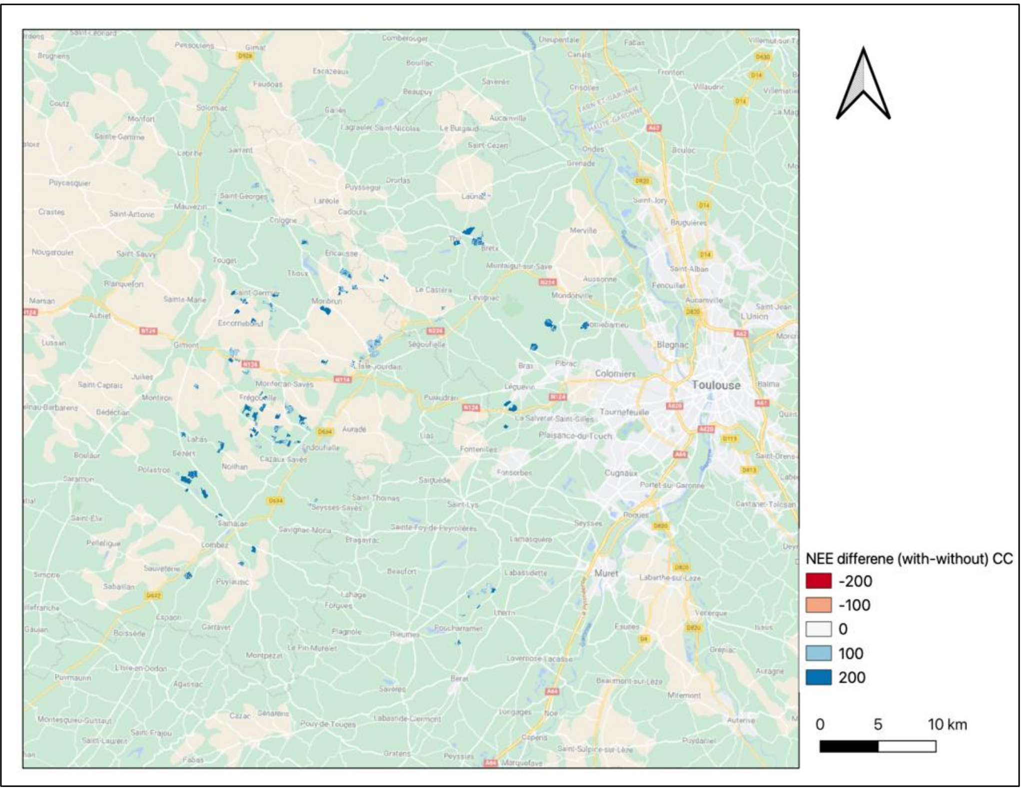
NEE : Bare soil + Maize



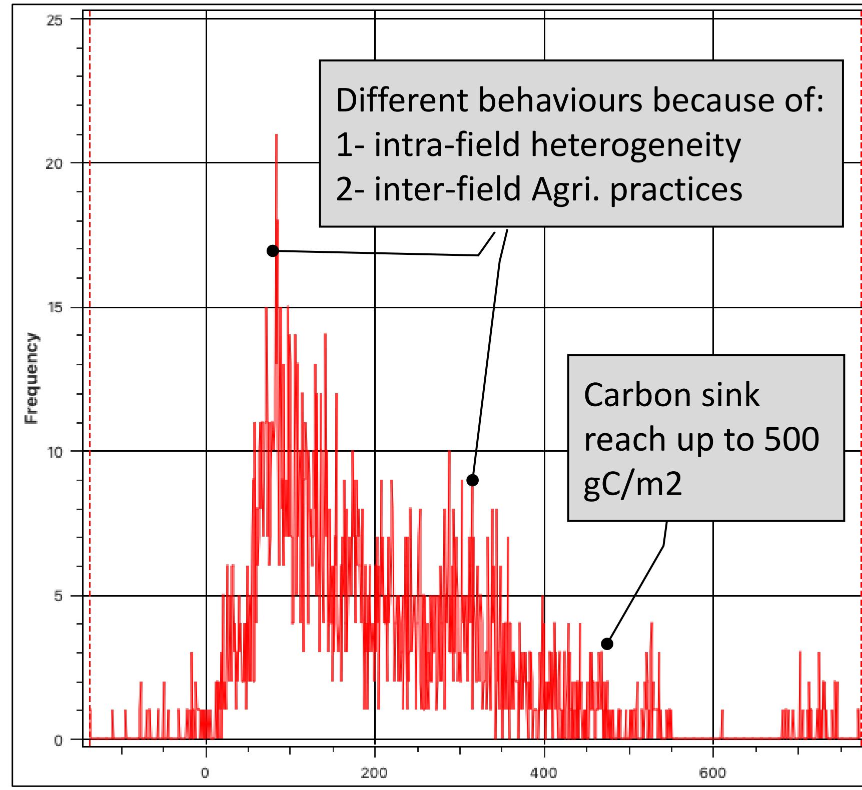
Realisation A. Al Bitar

Effect of cover crops on CO_2 fluxes

Map of NEE (+) – NEE (+)

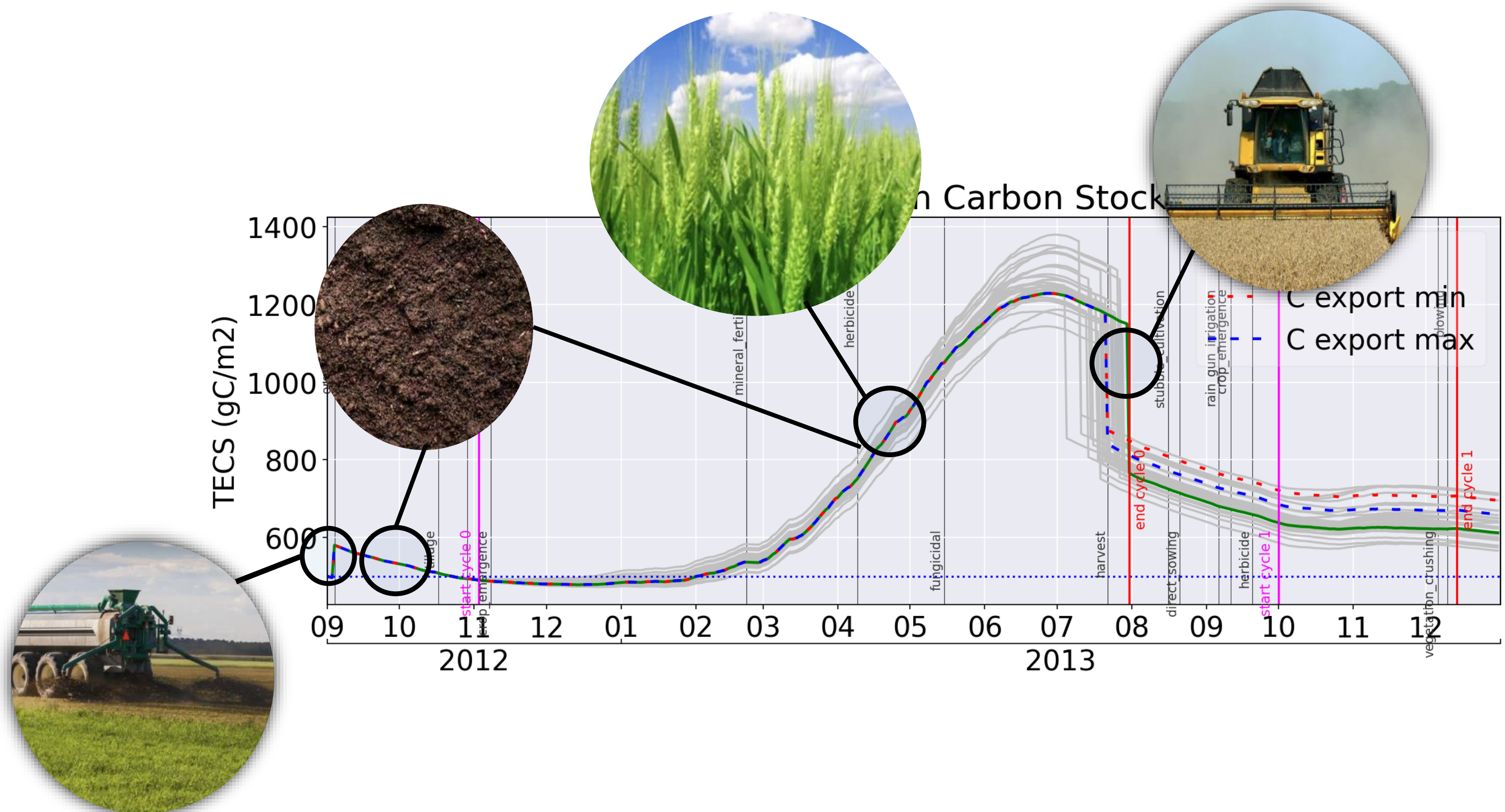


Histogramme NEE (+) – NEE (+)



Realisation A. Al Bitar

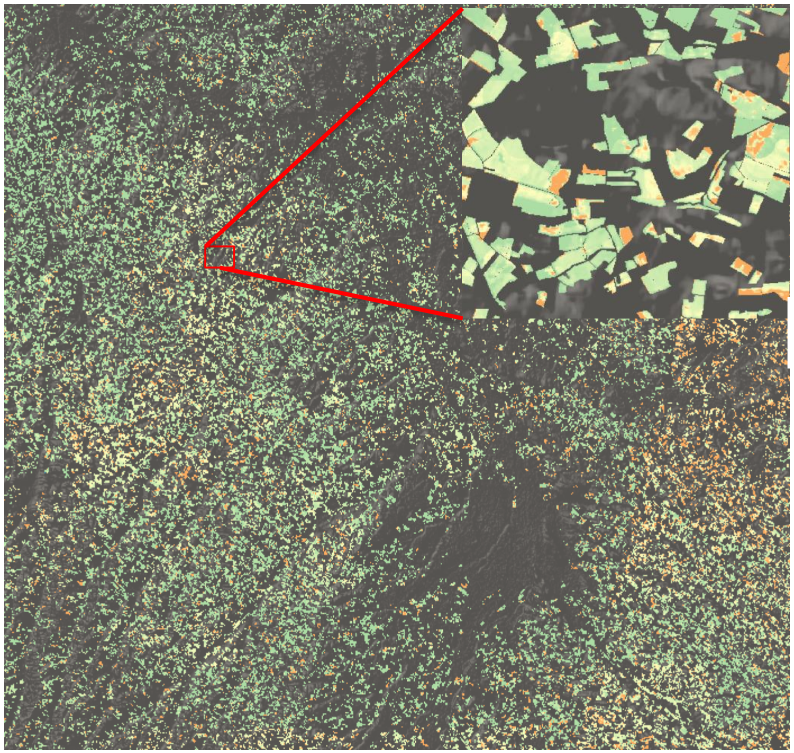
Dynamics assessment of the plot C budget



TECS = total ecosystem carbon stock

AgriCarbon-EO's output

Net annual CO_2 fluxes for 2018 straw cereals in South West France (10 m resolution) ➔ **4h of computing**



Net annual CO_2 flux (gC-CO_2/m²/yr)

NEE for wheat in 2017
- -125
- 150
- 425
- 700

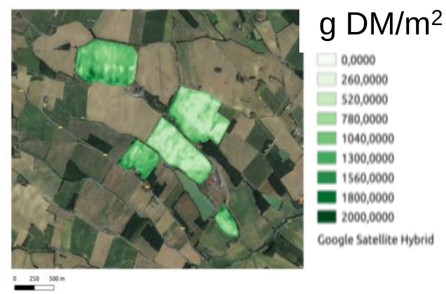
Google Terrain

Whole Sentinel 2 Tile (31TCJ)

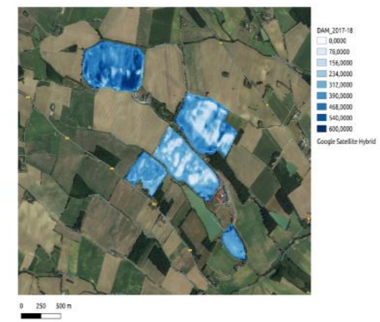
CO_2 fixation / soil C storag

CO_2 losses / soil C losses

Cover crop biomass



Uncertainty map



\+ farmer's data

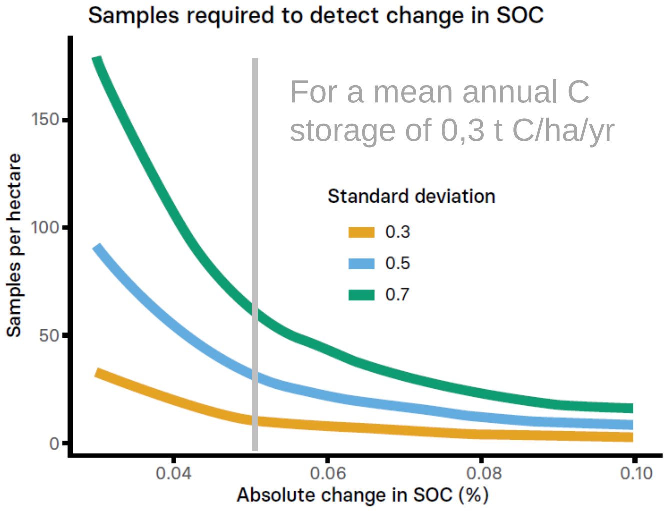
10m resolution C budget map for cover crop/maize/wheat crop rotations (Villeneuve farm, France)

Collab. with the Nataïs company (Naturellement popcorn project) ➔ farmers get a bonus according to the C they store in the soil with cover crops

Are 10 m resolution C budget estimates needed?

High resolution analysis is needed for:
- proper estimates of C budget assessments (+ intermediary variables, e.g. biomass, yield) and validation based on in-situ soil sampling given the strong spatial heterogeneity of soil and biomass inputs !!!!

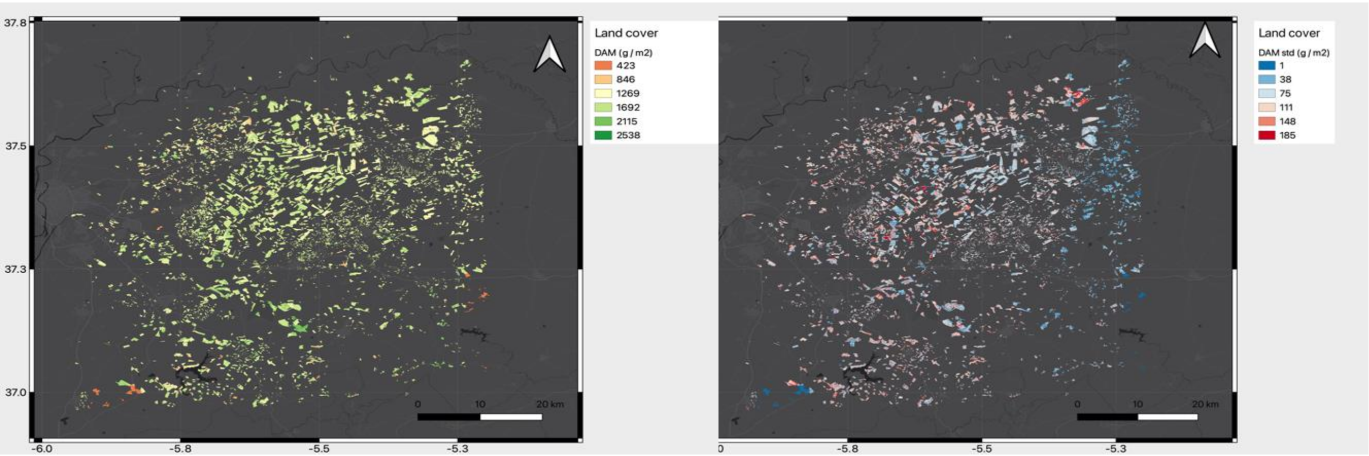
- Also possible to use these maps to define a soil sampling plan upstream of Carbon farming projects:
  ➔ More representative sampling of C storage/losses dynamics within plots/at farm level,
  ➔ Need to take fewer samples to assess the average C storage/losses of the plot/farm level ➔ less costly to analyse soil at farm level, otherwise…



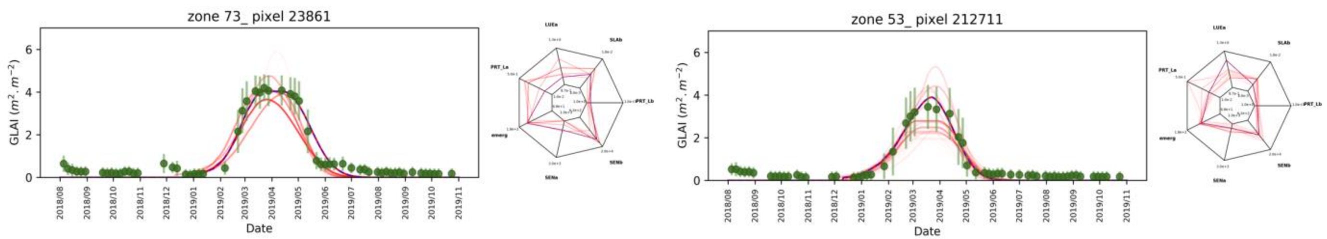
Need to collect 25 to 75 samples per hectare !!!

Transposability of the approach

Winter wheat biomass at 10m resolution near Sevilla



- Fully automated process (just provide LPIS)



Two examples of simulated (red) and observed satellite (green) GAI time series

- Good reproduction of vegetation cycles without model recalibration

Run Agricarbon EO over 1 Sentinel 2 tile (110 x 110 km)
➢**Computer 500Gb of memory 72 hearts**
➢**Less than 24h, including download of the data : SAFYE-CO2 simulations took about ± 3h**

Realisation T. Wijmer & A. Al Bitar

Future improvements

- This approach currently only allows for the estimation of biomasses on the main crops (wheat, maize, sunflower, rapeseed) and some cover crops ➔ extend the approach to other species or even temporary grassland to simulate most crop rotations (CROP 2021 action in progress, 1 PhD begining),
- Use of SAR satellite data (Sentinel-1) to monitor crop/canopy development even in cloudy conditions ➔ more operational approach (1 PhD in collab. With the NetCarbon company),
- Use high resolution soil properties maps from in-situ spectroscopy or remote sensing ➔ improved precision and representativeness of soil data input to the AMG soil model (e.g. European EJP Soil Steropes project).

- Develop a graphical interface: user-friendly use, API to automatise farmer's management data, visualization of results…

Conclusions concerning AgriCarbon-EO/SAFYE-CO2

- Based on (mainly) open data & tools, C and water budget components can be produced at pixel/plot scale over large territories,
- Offers high levels of accuracy + uncertainty on the C budget components and provides useful indicators (yield, biomass, water requirements) + effect of management changes,
- Yet soil organic C stock changes still need to be validated against in-situ soil sampling (no data availlable yet),
- Could be used in different context : CAP, NDCs (national inventories), voluntary C market, insetting (annual C budget estimates are needed),
- Main limitations :
  - this approach requires few farmer's data (organic amendments, straw management, irrigation) but that are difficult to obtain at large scale although tools exist (APIs, Farm Management Information System) but problem with management of farmer's consent, not all use FMIS…
  - calibration/validation process required for each new crop specie ➔ long process mainly because of the lack on in-situ data,
  - Current soil products (maps of soil properties) are not accurate enough yet ! ➔ digital soil mapping (e.g. with Sentinel2/hyperspectral) could help !

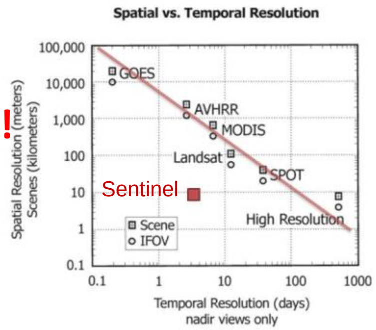
What about spatialised analysis of albedo ?

The exemple of the Sentinel 1 & 2 satellites

Sentinel 1

(10 m, 6j, SAR)

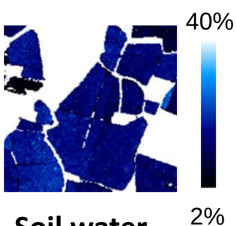
A revolution !!!



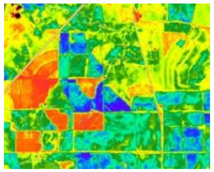
Sentinel 2

(**10 m, 5j, Optical**)

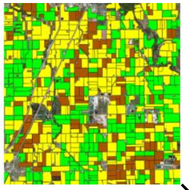
Clear sky or cloudy conditions Rugosity & surface humidity	measured parameters	Clear sky conditions Reflectances



Soil water content



Biomass



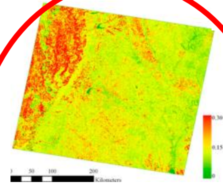
Soil work

Dynamic mapping

fusion

Land use

Leaf area index/ phenology



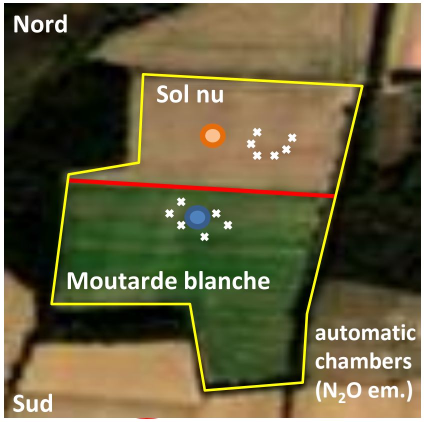
Albedo ??

Not yet and unlikely
➔ low/medium resolution
(e.g. MODIS product, 500m)

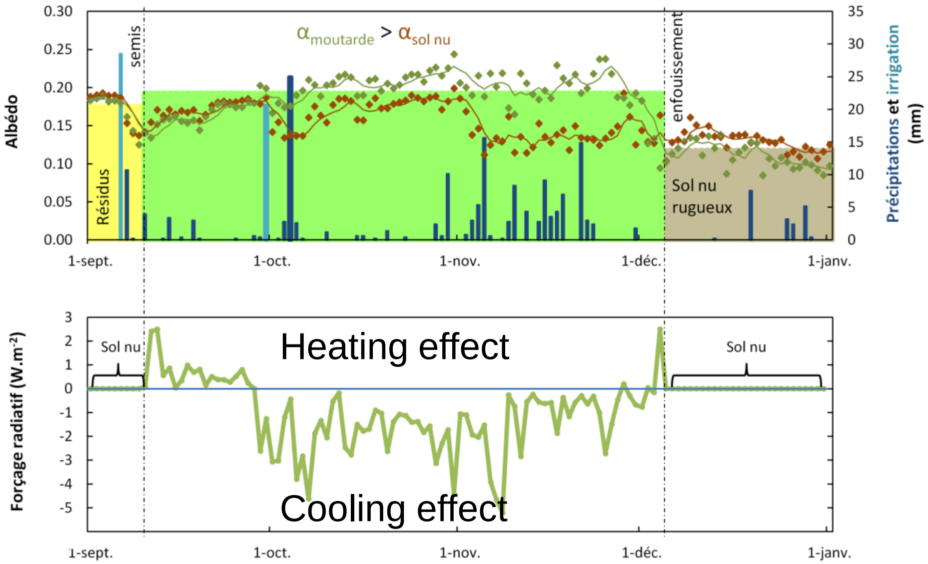
How can we use this wealth of information to answer scientific and societal questions?

Albedo effect of cover crops

Cover crops generally increase the amount of solar radiation (short wavelengths) returned to space relative to bare soil. Albedo change from -3% to +20% (Kaye & Quemada, 2017).



Lamasquère site (31) in 2013
(PhD M. Ferlicoq)



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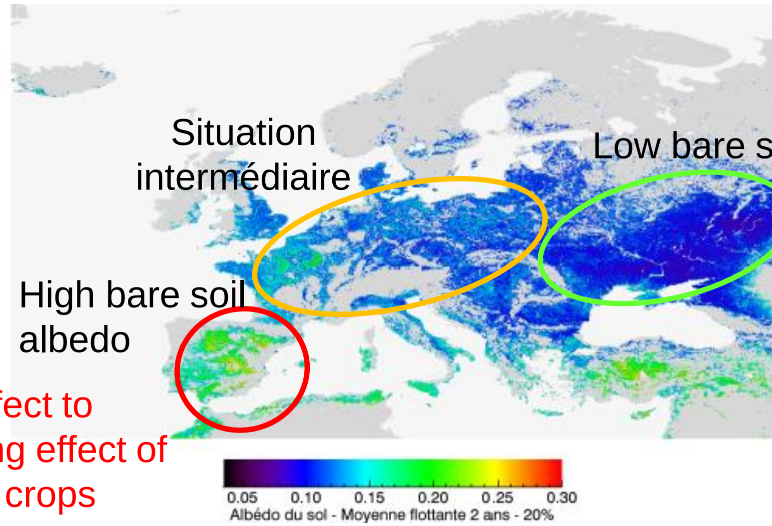
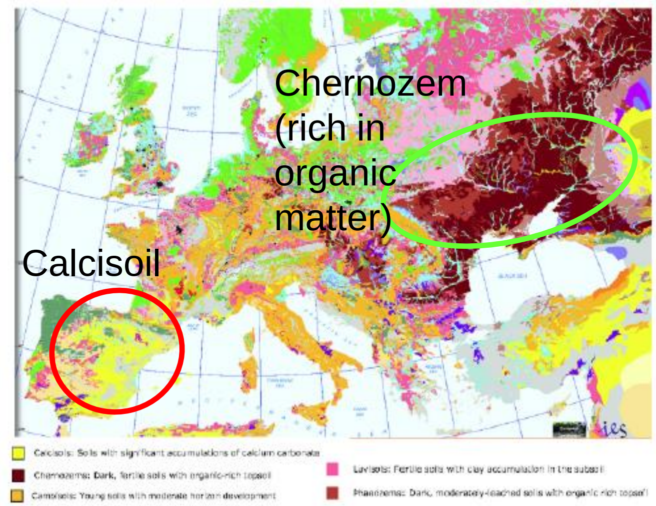


Bare soil albedo maps following desagregation of MODIS data (Carrer et al., 2012)

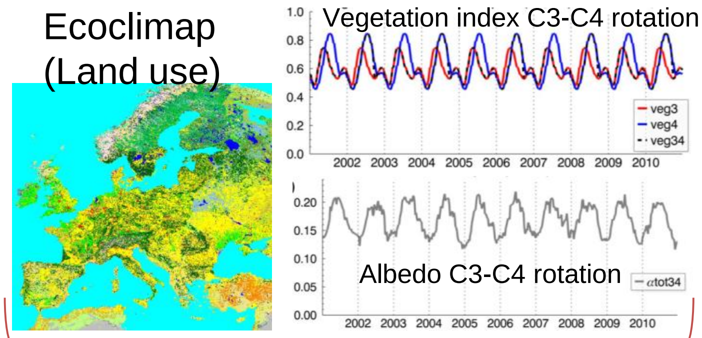


Remote sensing can be very useful in identifying where cover crops should be introduced to mitigate climate change via the albedo effect (Carrer et al., 2018, Pique et al. submitted).

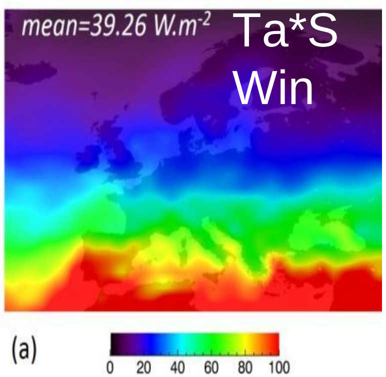
Analysis of the cover crop albedo effect (vs bare soil)

Carrer et al. (2018) in ERL

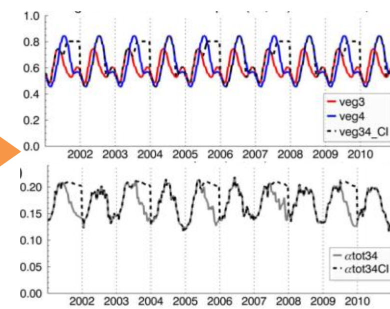
Ecoclimap (Land use)



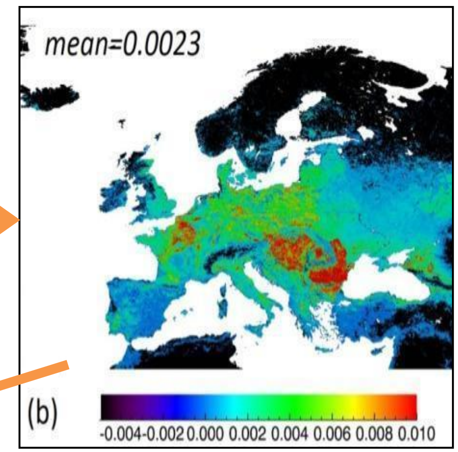
Desagregated vegetation index, bare soil albedo & vegetation albedo (snow free) derived from MODIS data at 5*5 km (Kalman filter ; *Carrer et al., 2014*) ➔ albedo of C3-C4 crop rotation



Analysis of where and when cover crops are introduced



Daily albedo increase with cover crops



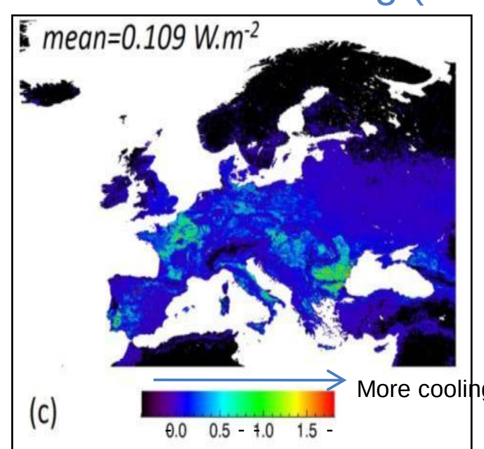
Daily global radiation& atmospheric transmittance (ERA-5)

RFCC

Radiative Forcing of Cover Crop

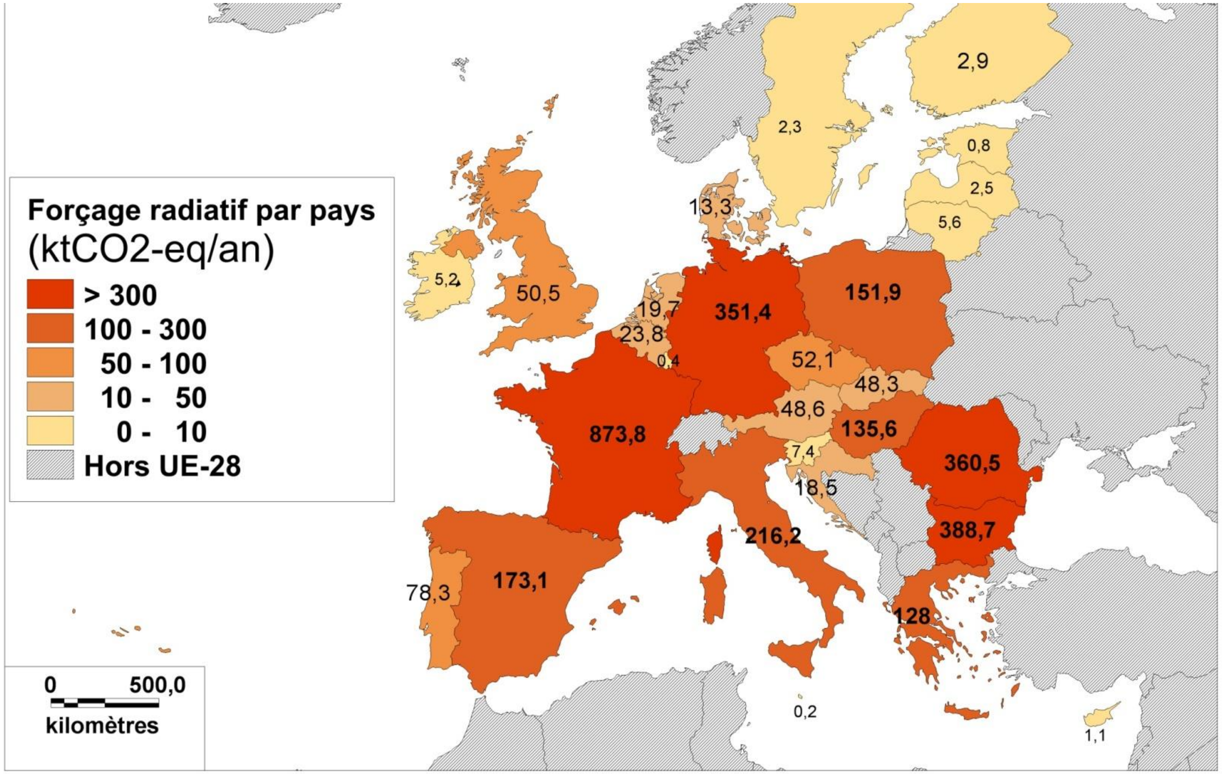
$$RF\alpha = - Rg \times TA \times \Delta\alpha$$

Radiative forcing ($W.m^{-2}$)



Albedo effect of 3 month cover crop introduction in eq-CO_2

(Carrer et al. 2018)



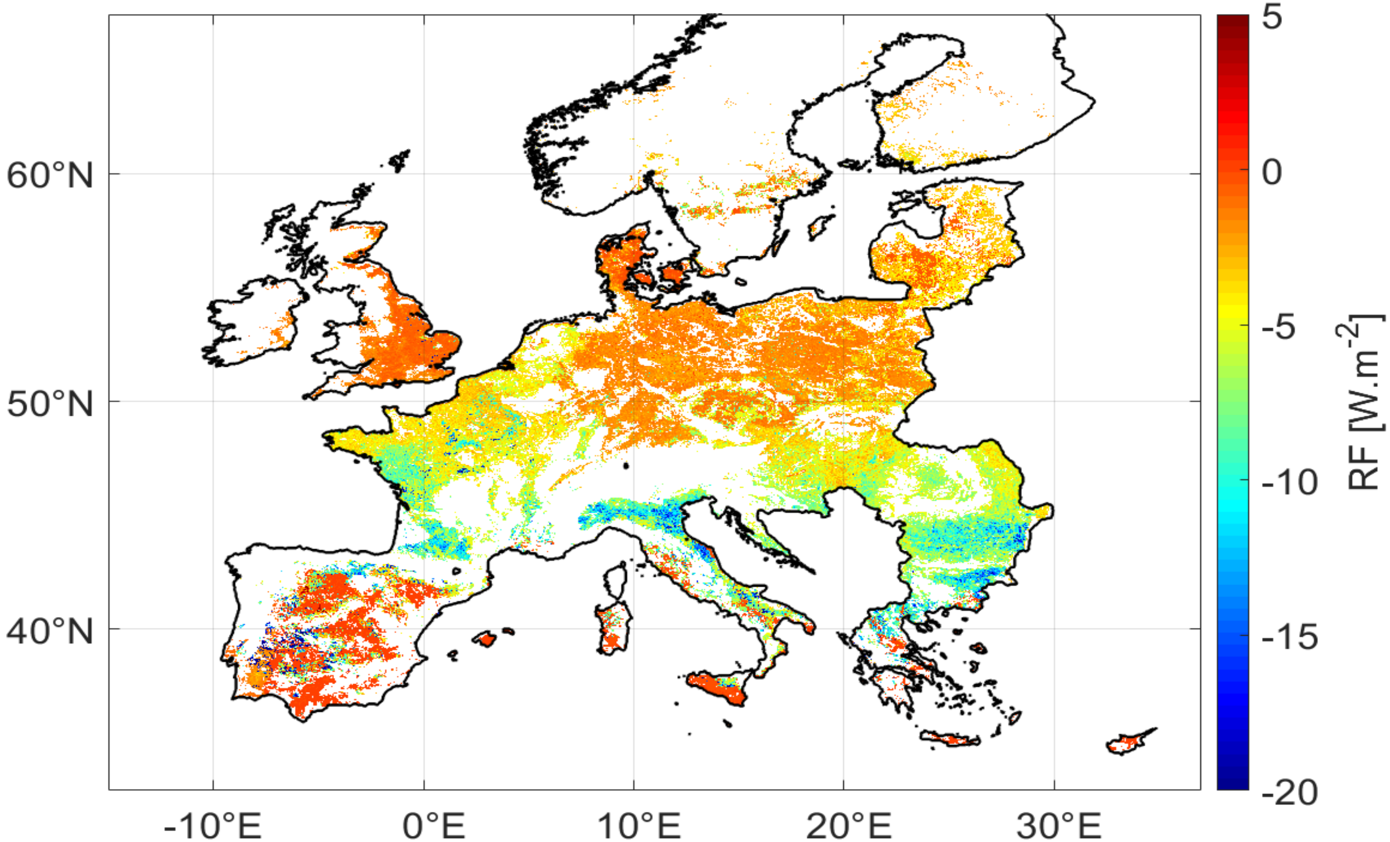
- 3 month duration cover crop scenario ➔ the cumulative RFα over EU-28 is 3.2 (2.9) $MtCO_2$-eq.year^{-1}.

- Same but accounting for rain limitation ➔ the cumulative RFα over EU-28 was 2.3 (2.1) $MtCO_2$-eq.year^{-1}

- 6 month duration cover crop scenario + rain limitation ➔ the cumulative RFα over EU-28 was 4.3 (4.0) $MtCO_2$-eq.year^{-1} *i.e.* a compensation of up to 1.0 (0.9)% of the EU-28 agricultural GHG emissions.

The countries with the greatest potential for albedo effect linked to the introduction of CC are France, Romania, Bulgaria and Germany

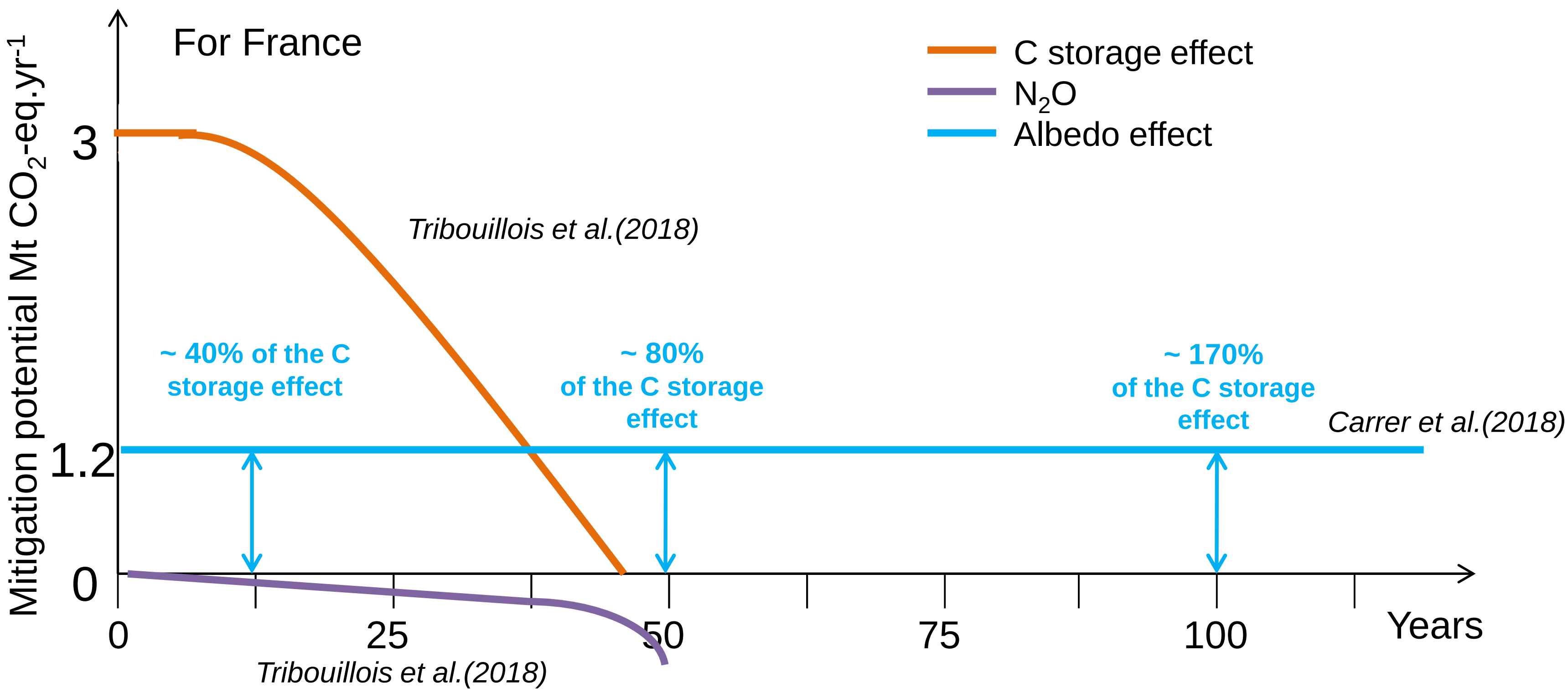
Albedo effect of cover crop maximum coverage



Equivalent to 6,7 Mt CO_2-eq/yr* on average over this area of study but in some areas like Spain, Sicilia and Greece cover crops increase surface albedo (anyway those areas are too dry to implement them…). Yet 3 times more thans with a 3 month cover crop scenario

* against 31 Mt CO_2eq/yr for the cover crop C storage effect in France only with the same scenario of introduction

Comparison of cover crop C and α effects on the long term vs short terms

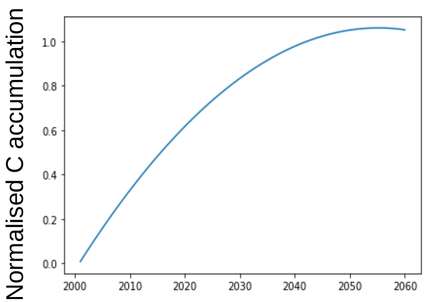


In the short term the albedo effect is lower than the storage effect of C intermediate crops but integrated over 100 years it is the reverse

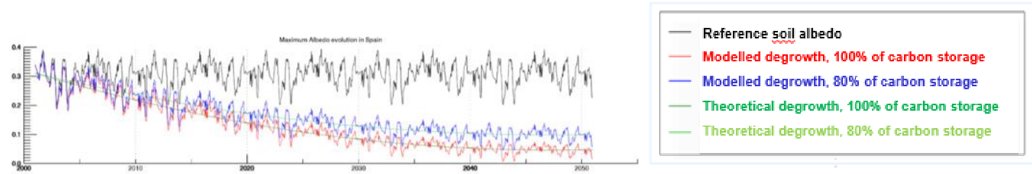
Comparison of cover crop C and α effects on the long term vs short terms

However…

Gaétan Pique's PhD (paper in prep)



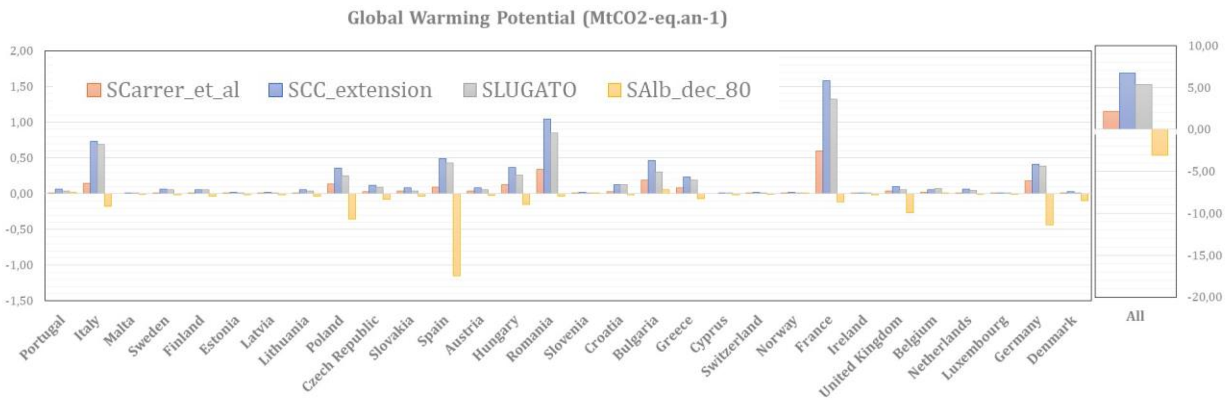
Adapted from Tribouillois et al (2018) and considering Corg max similar to Romanian soils



Modelled bare soil albedo decrease takes into account the progressive incorporation of organic matters in the soil (in the whole soil profile while in reality OM accumulates first in the top soil)

Same method as in Carrer et al. (2018) but over 50 years (current climate) considering several scenarii:

- 3 month CC
- Extension cover crop (as in *Pellerin et al. 2019*)
- Extension CC + soil darkening with a realistic scenario (modelled with DayCent as in Lugato et al. 2020),
- Extension CC + soil darkening considering albedo decrease till 80% of the lowest soil albedo value in Europe



Once cover crop are adopted (or other practices increasing soil organic C content), soil should be covered permanently to avoid this drawback. This can be achieved by different means (e.g. crop residues)

Conclusion

Multi-criteria territorial diagnostics are now possible through remote sensing (inventory):

➔ Analyses of crop rotations, some management practices (e.g. irrigation, tillage, cover crop, weed destruction, etc.)
➔Estimation of albedo, biomass, soil moisture at the plot or even in sub-plot (precision agriculture),

Limits: some practices are not detectable by remote sensing (e.g. most pesticides applications, straw export, amount of organic amendments) ➔ FMIS

Possible to establish more advanced indicators through by assimilating multi-temporal remote sensing data in crop models :

➔ Yield, biomass, irrigation needs (e.g. Battude et al. 2015, Demarez, 2018),
➔ CO_2 fluxes and the other components of cropland C budget (SAFYE-CO2…),
➔ Albedo effects following changes in land cover & management,

Essential tools to guide/objectify our choice of practice changes and compromises to be achieved according to local issues (e.g. production/storage of C/water requirements, cover crop C vs albedo effects on the short-ter/long-term…)

➔ towards a more informed territorial agroecology

Key messages

- It is urgent to reduce the gap between agronomists/soil scientists… and Earth System modellers to obtain more realistic quantification of the true climatic effect of cropland management changes,

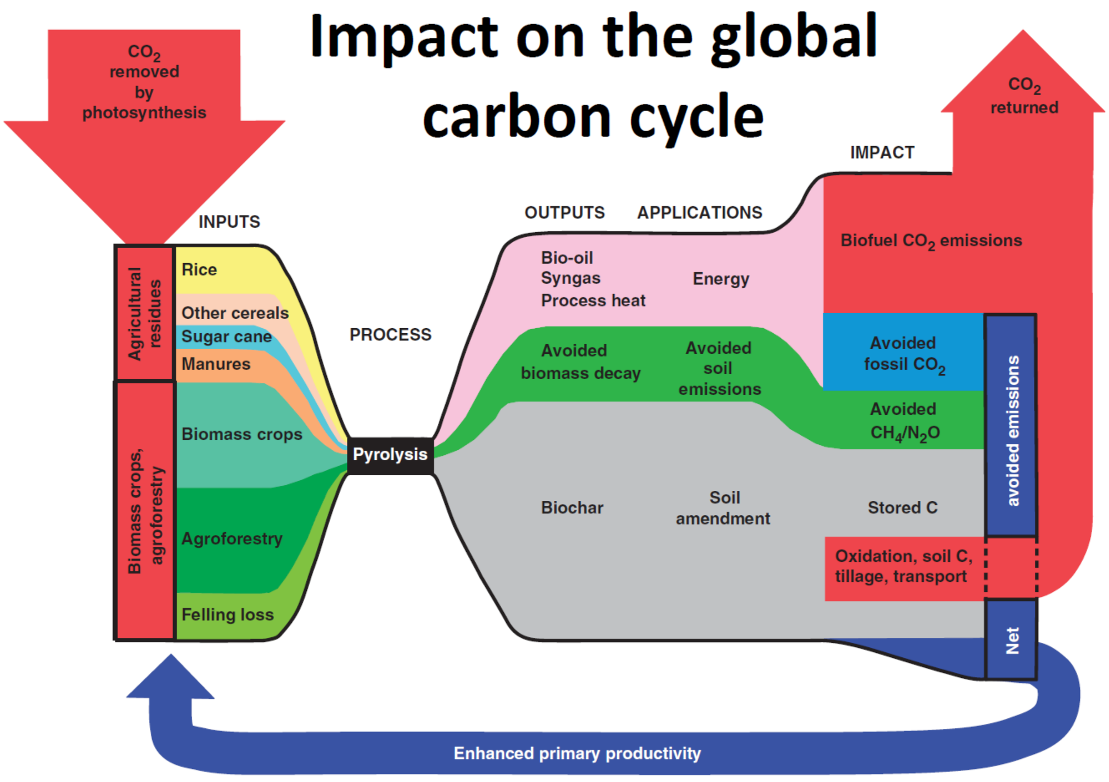
- We should push toward policies that account for biogeophysical effects to reach climate neutrality,

- Biogeochemical and biogeophysical effects should be analysed jointly ➔ more efficient climate change mitigation strategies by identifying synergies or antagonisms between effects,

- And yes, approaches combining remote sensing and crop modelling provide usefull insight for assessing the effect of cropland management changes on the C, water and energy (albedo) budgets and for identify where to implement which management change.

Thanks again for your attention !!!

Biogeochemical effects induced by biochar



MSTP = 1.8 Pg CO_2-C_e per year = 12% anthropogenic emissions

"..without endangering food security, habitat or soil conservation."

(Woolf et al., 2010)

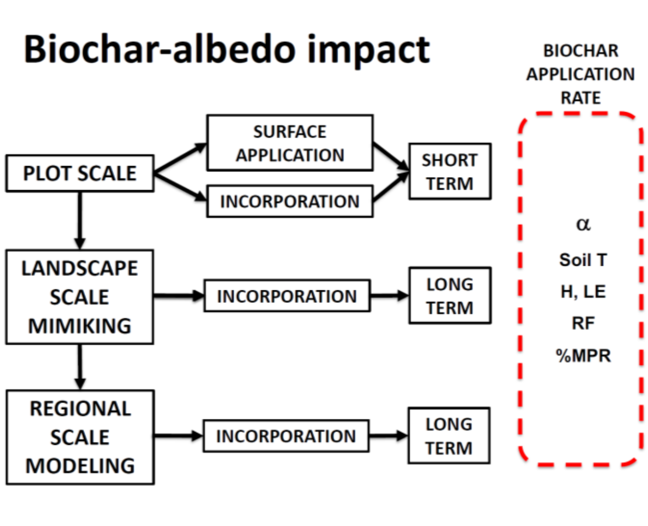
FACTS

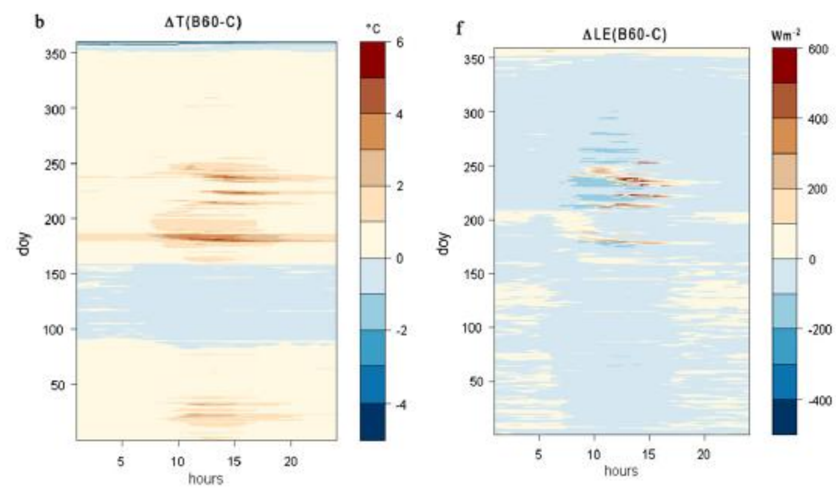
- Biochar is effective for CC mitigation,
- it increase yield (Jeffery et al. 2011)

Biophysical effects induced by biochar (drawbacks)

See Genesio (2012; 2016) Bozzi et al (2015) and https://www.youtube.com/watch?v=eph3hCUlRNY

- 40% albedo changes (yearly mean 0.08-0.12 for 30-60t ha^{-1})
- Anomaly in surface temperature (seasonal mode)
- Increased evapotranspiration
- Changes in energy partitioning





Implications

- Accelerated germination
- Reduction of mitigation benefit of biochar

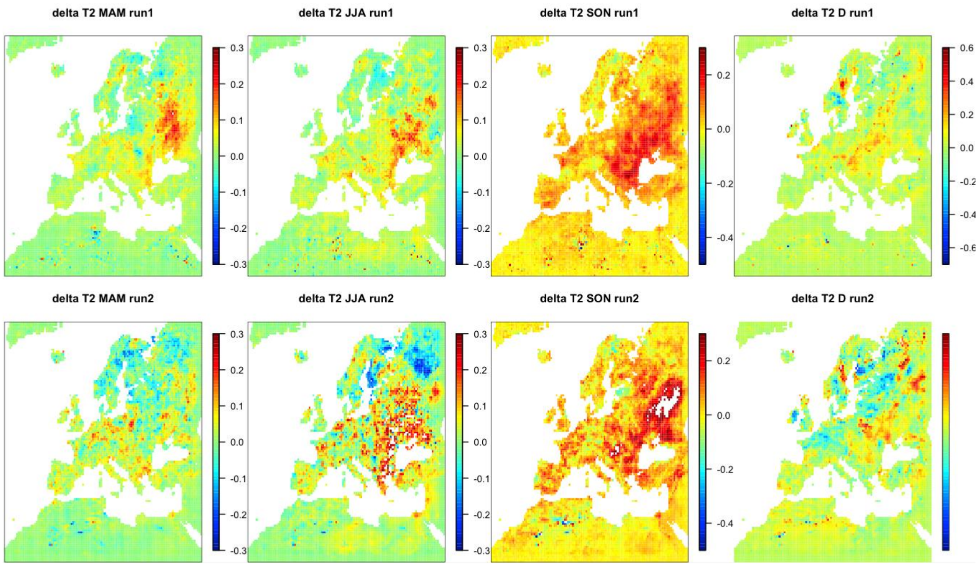
Biophysical effects induced by biochar

See Genesio (2012; 2016) Bozzi et al (2015) and https://www.youtube.com/watch?v=eph3hCUlRNY

Regional modeling of biochar application

• perturbing the arable land albedo scheme in WRF model (1 year)

• significant impact on surface temperature in Eastern Europe



RECOMMENDATIONS

• Biochar application with Cover Crops and residue management,

• Optimize agronomic practices and choose the appropriate locations (dark soils YES, bright soils NO),

• Avoid Black Carbon aerosol release during production and application.