Modelling the greenhouse gas balance of agro-ecosystems in Europe

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Outline

1- Introduction

- Context
- Biophysical processes underlying greenhouse gas exchanges
- Methods to quantify greenhouse gas fluxes
- Objectives and modelling approach

2- Modelling and monitoring of greenhouse gas fluxes

- The CERES-EGC model
- Experimental measurements
- Bayesian calibration and model evaluation

3- Results and discussion

- Bayesian calibration of the N_2O and CO_2 exchange modules
- Evaluation of prediction error
- Model application for prediction of greenhouse gas balance

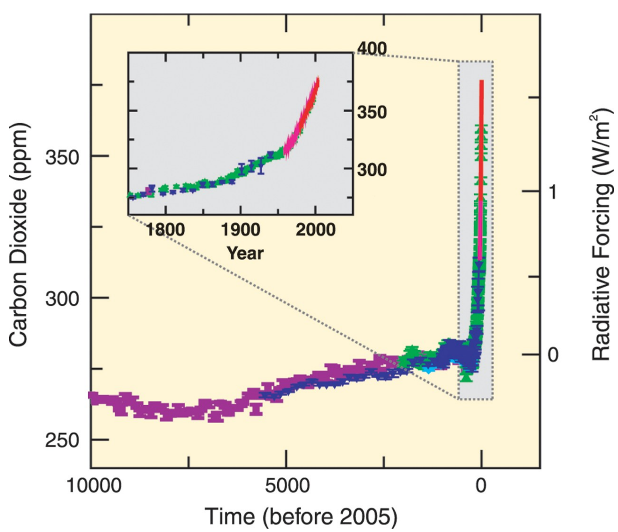
4- Conclusions and perspectives

1- Introduction

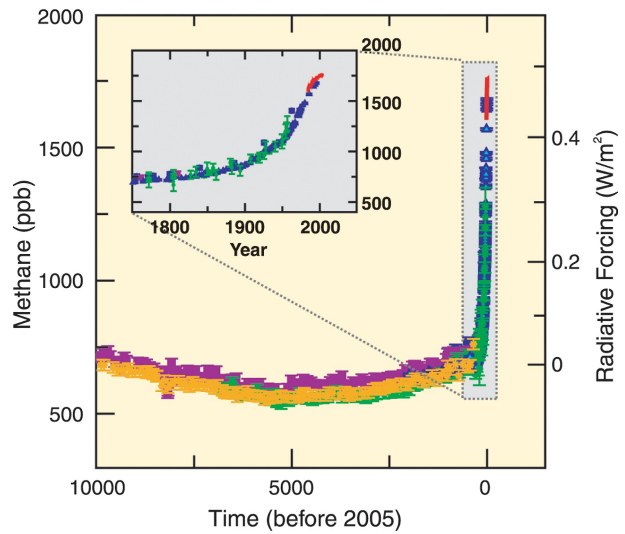
« Most of the observed increase in global average temperature since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations »

IPCC report, 2007

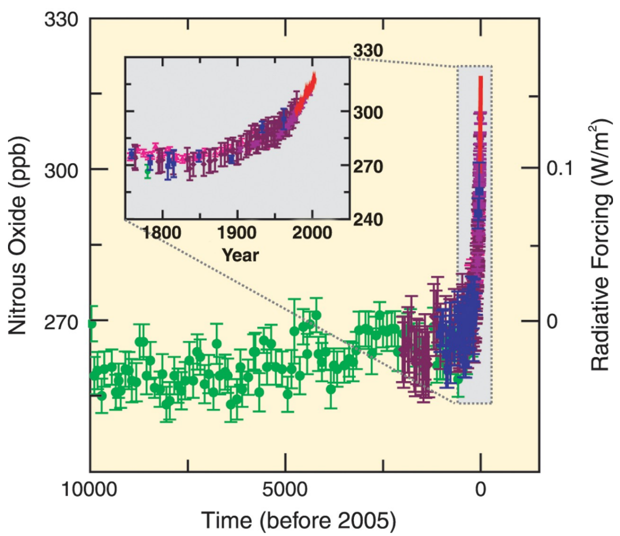
CO_2



CH_4

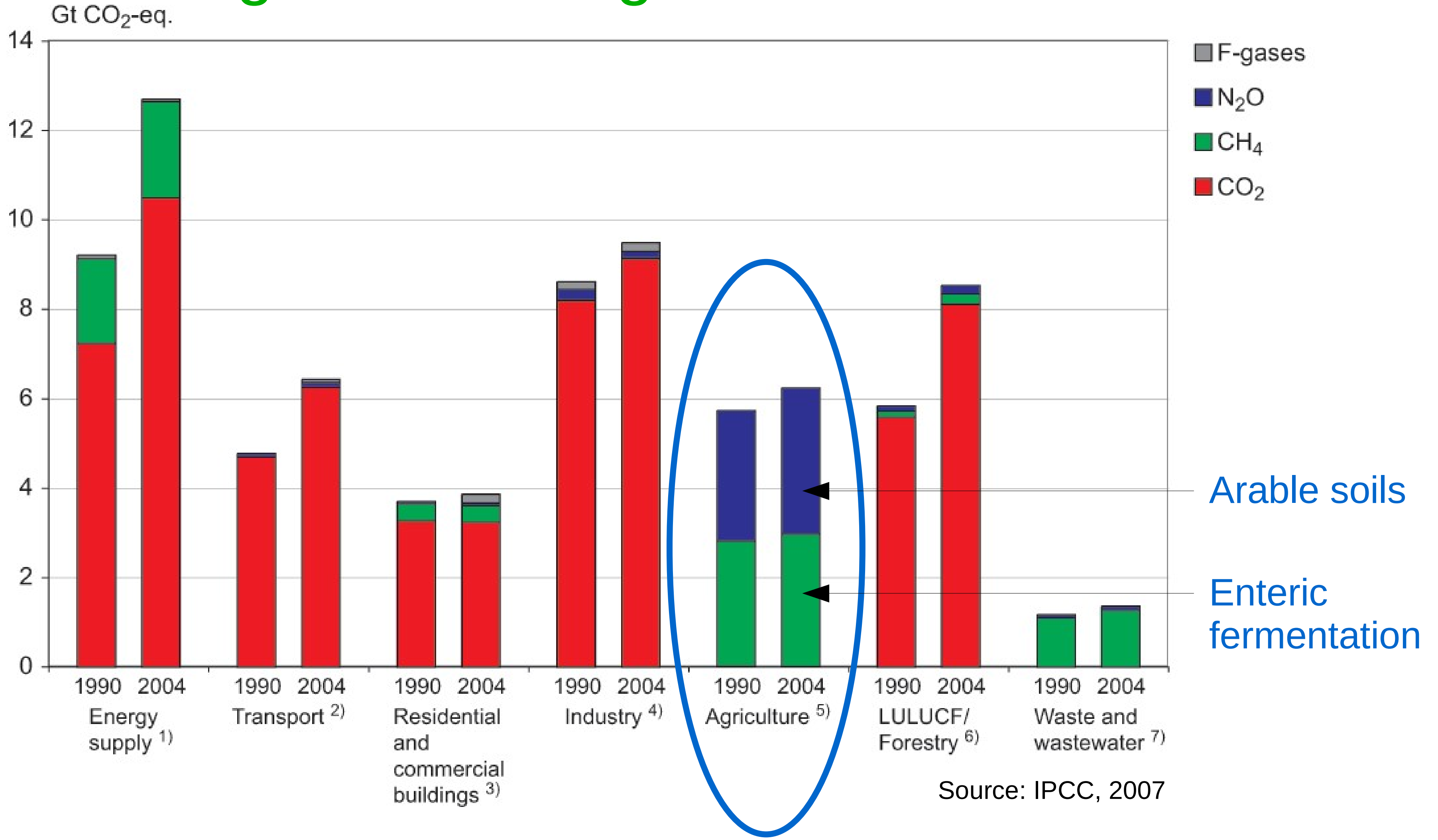


N_2O



Global warming potential relative to CO_2:	**1**	**25**	**298**

Contribution of agriculture to greenhouse gas emissions



Source: IPCC, 2007

Agriculture contributes 10-12 % of anthropogenic greenhouse gas emissions mainly from N_2O and CH_4 emissions

But this share is highly uncertain ! (+/- 50%)

What are the societal demands?

- Increased awareness of society and public authorities of climate change and of the necessity to abate greenhouse gas emissions.

- Demands to minimize agriculture's footprint

- Growing demands for methods and tools to evaluate the greenhouse gas balance of agricultural systems and products

- Inventorying greenhouse gas emissions to design abatement measures
  (United Nations Framework Convention on Climate Change, Kyoto protocol)

- Assessing the integrated balance of production systems with a life-cycle approach
  (Greenhouse gas balance of farms, environmental labelling...)

- Assessing the environmental balance of bioenergies
  (Criteria of sustainability for biofuel production)

What are the scientific challenges?

- ***QUANTIFYING*** :
  - To gain a capacity to quantify greenhouse gas emissions for a range of environmental conditions and agricultural practices
  - Based on monitoring and modelling methods

- ***PREDICTING*** :
  - To reduce the uncertainty of model estimates
  - To extrapolate over time and space

- ***REDUCING*** :
  - To propose management strategies that mitigate the global warming potential of cropping systems

The NitroEurope project

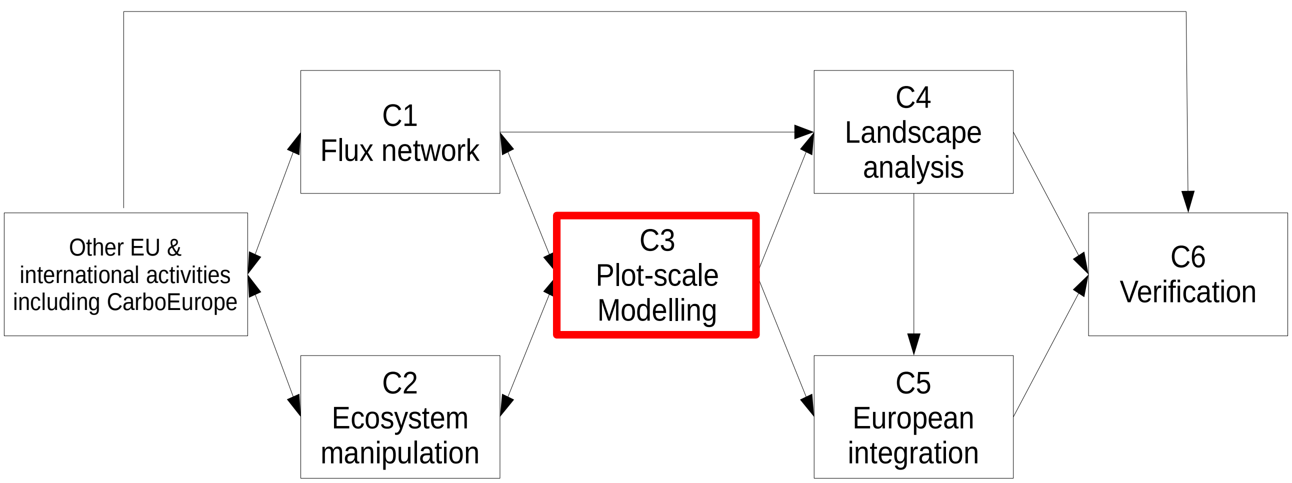
The nitrogen cycle and its influence on the European greenhouse gas balance

25 countries, 60 partner institutes

What is the effect of reactive nitrogen supply on net greenhouse gas budgets for Europe?

NitroEurope IP

Organised in 6 scientific components:

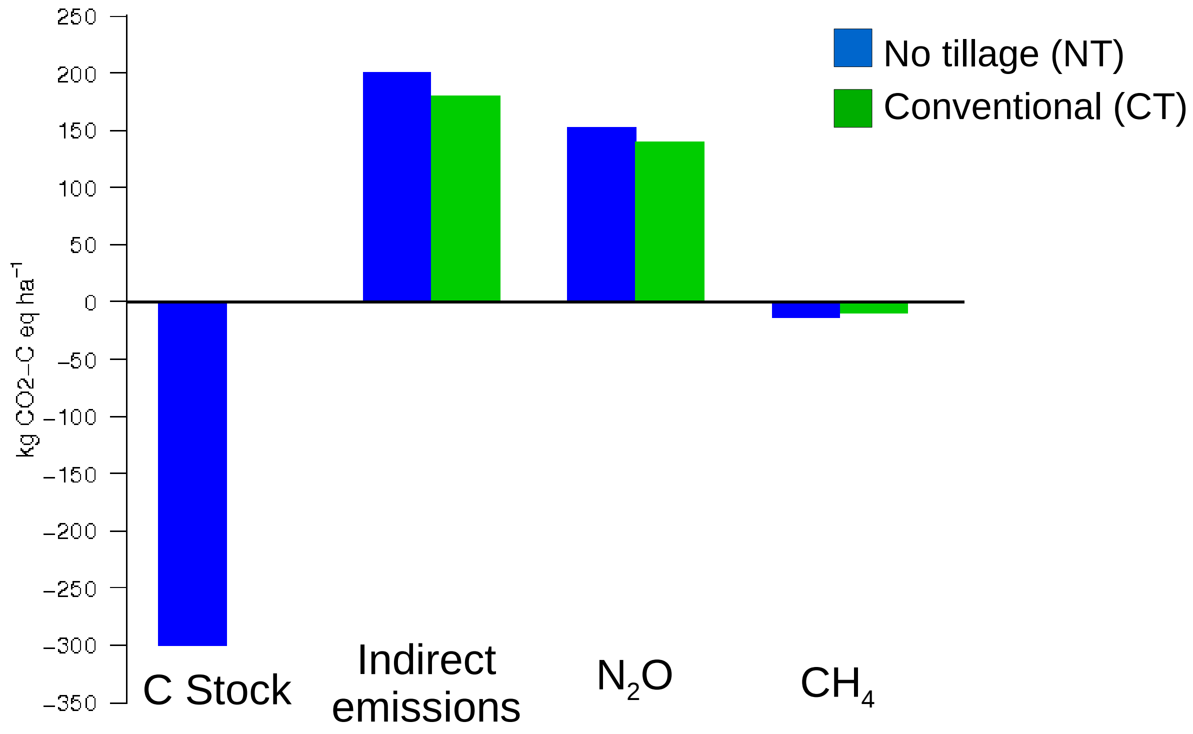


Objectives of component 3

- Uncertainty of ecosystem models
- Simulation of GHG fluxes of C1 sites
- Testing scenarios of mitigation
- Spatial extrapolation

Contribution of crop production to GHG emissions

Maize-Soybean-Wheat system
(Robertson et al., 2000)

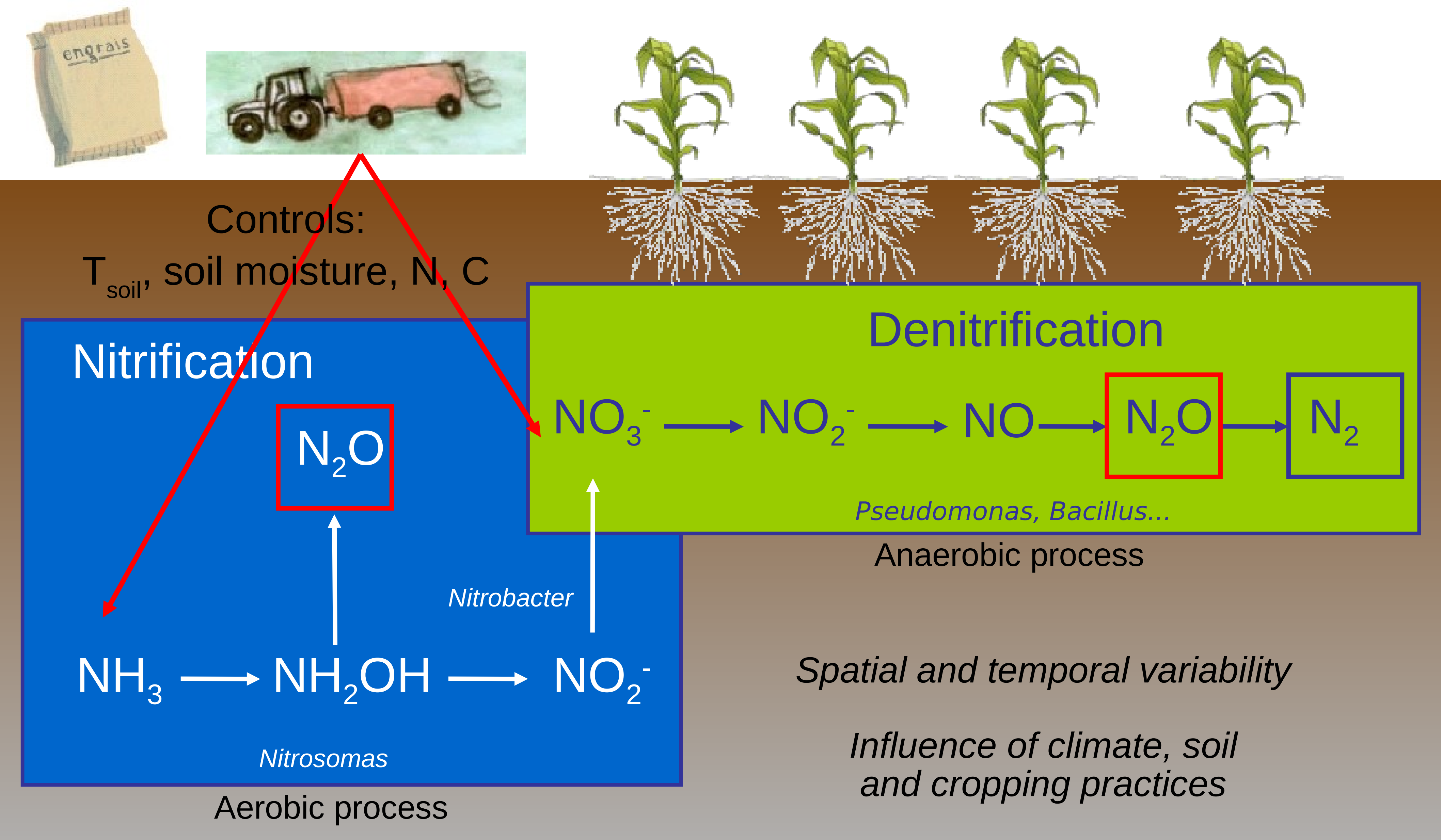


Global warming potential:

NT: 40 kg CO_2-C eq ha^{-1}
CT: 310 kg CO_2-C eq ha^{-1}

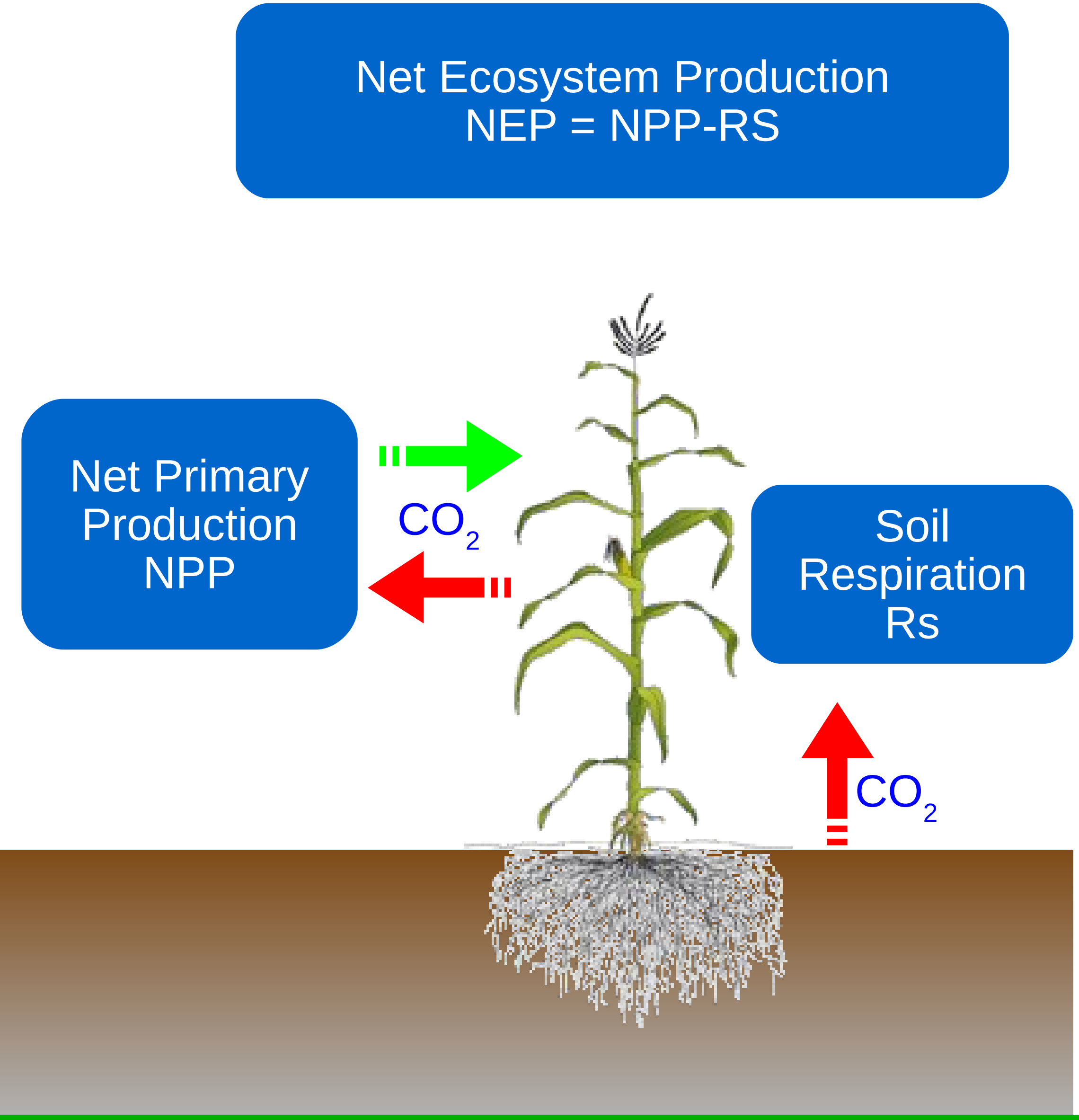
- 3 crucial points
  - Variation in ecosystem C stock
  - N_2O emissions
  - Indirect emissions (upstream)
- Need for more generic methods

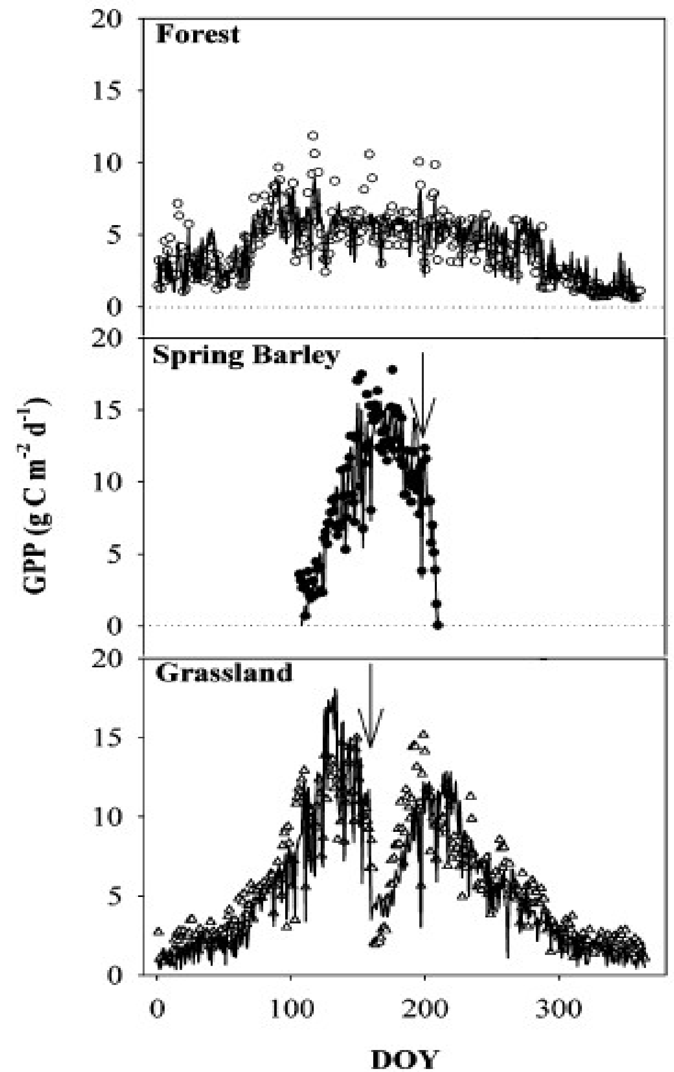
Processes of N_2O emissions



Processes of CO_2 exchanges

CO_2 fluxes of agro-ecosystems are controlled by management practices





Black et al., 2006

How estimate the greenhouse gas budget?

- **Field measurements**

Process study

Costly and limited spatial/temporal cover

Micrometeorologic methods
Chamber technic

(Robertson et al., 2000)

- **Emission factors**

Easy to use

Highly uncertain

EF_1 = 1 %
(0.3-3 %)

$N_2O\text{-}N_{N\ inputs}$ = {FSN + FON + FRR + FMOS} . EF_1

FSN: Synthetic fertilisers; FON: Organic fertilisers; FRR: Crop residues; FMOS: Mineralisation of SOM

(IPCC, 2006 – Tier 1)

- **Agro-ecosystem modelling**

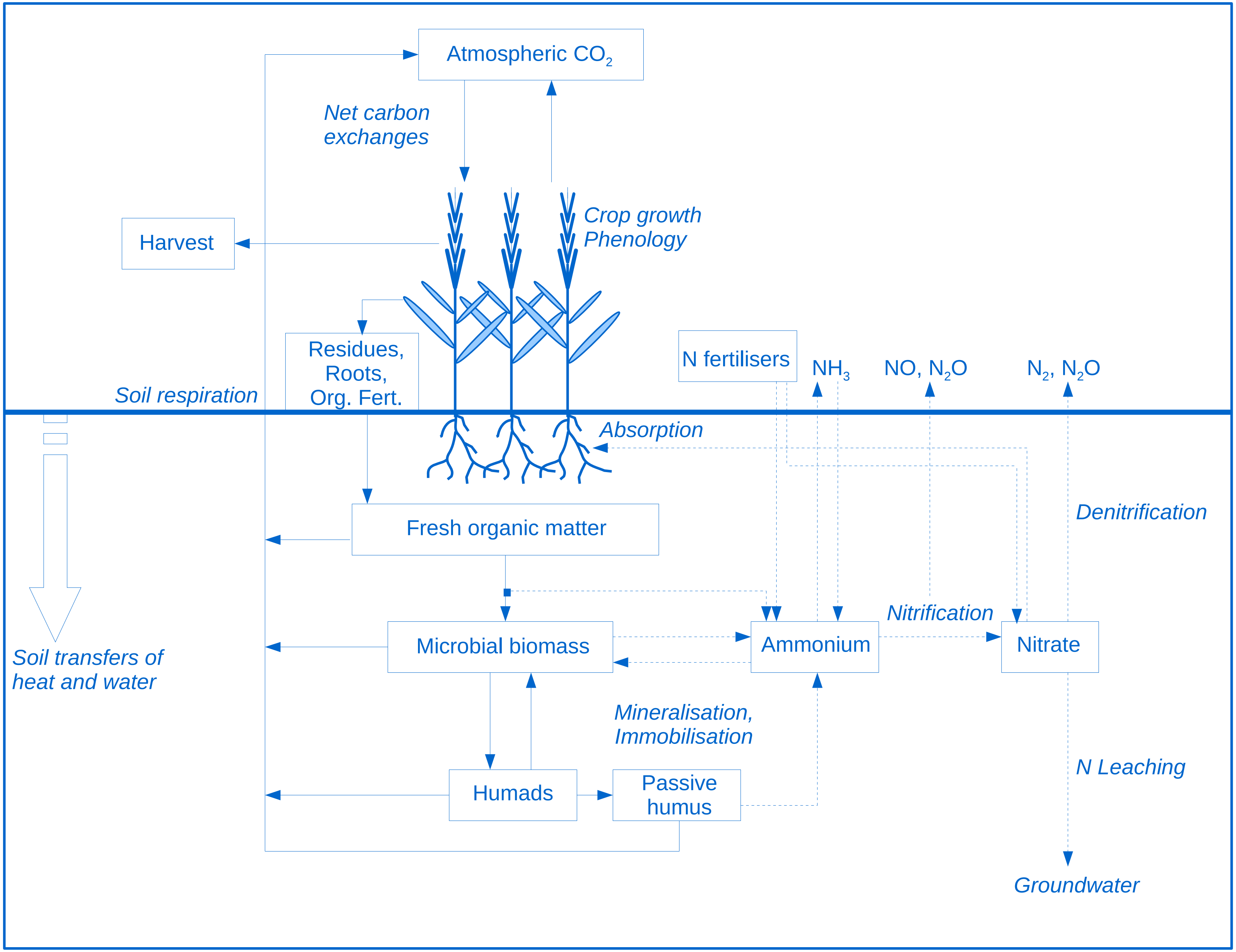
Accounts for local pedoclimatic conditions and agricultural practices (IPCC, 2006 – Tier 3)

Implementation is complex

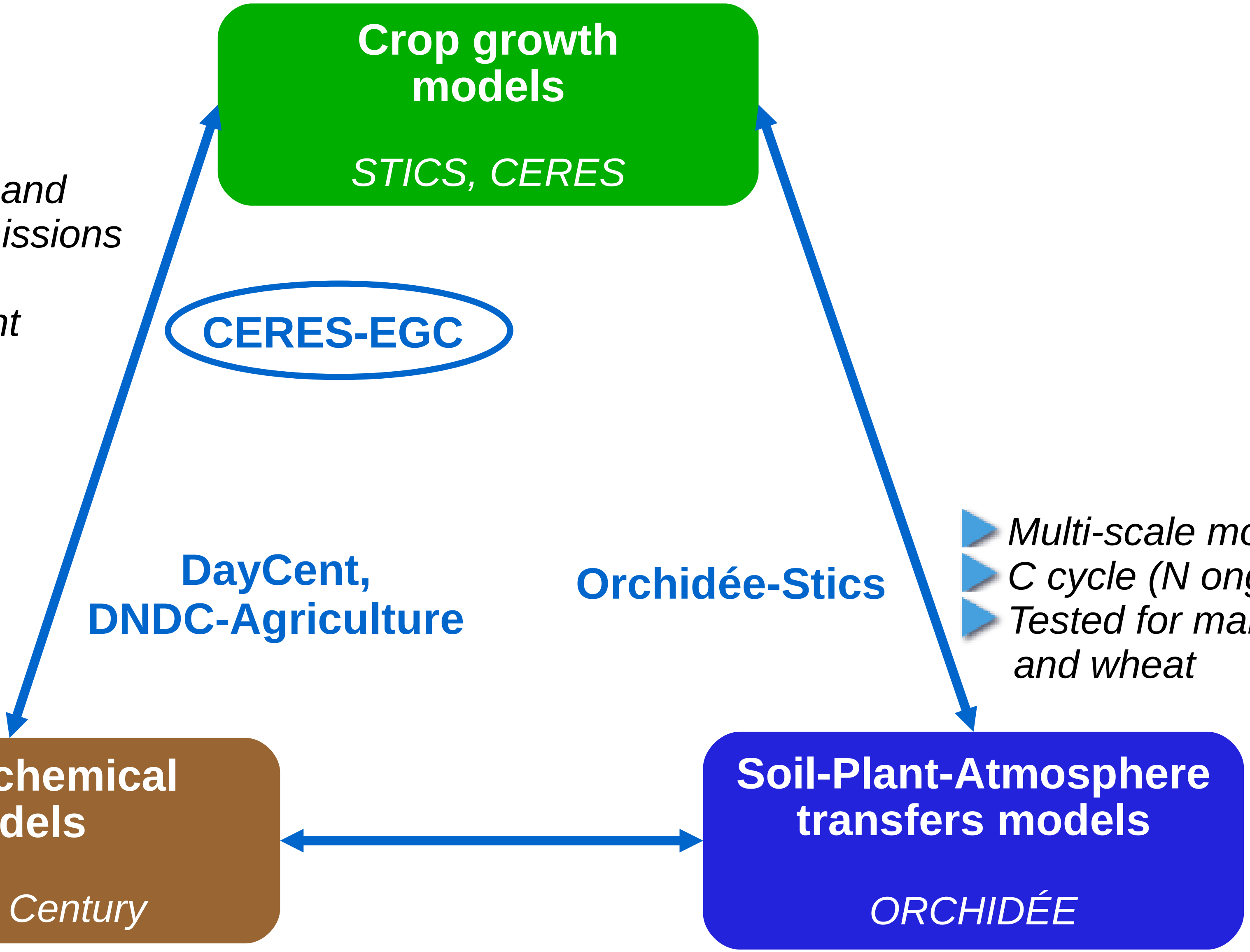
CERES-EGC
DNDC
DAYCENT

Gabrielle et al., 2006
Del Grosso et al, 2008
Li et al.,2005

Agro-ecosystem modelling



Agro-ecosystem models



- *Crop productivity and environmental emissions*
- *Main crop types*
- *Crop management*
- *C-N cycles*

- *Multi-ecosystem Models*

- *Multi-scale model*
- *C cycle (N ongoing)*
- *Tested for maize and wheat*

Objectives

To model the exchanges of N_2O and CO_2 at the field-scale to predict the global warming potential of agro-ecosystems

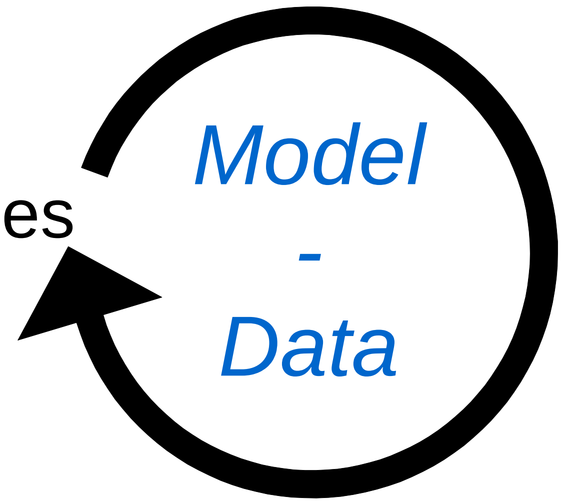
1- To improve the predictions of N_2O emissions

2- To improve the predictions of net CO_2 exchanges

3- To estimate the global warming potential of cropping systems

Modelling approach based on a loop of model improvement

Processes



1-Calibration

- Parameter estimation of the N_2O emission module
- Parameter estimation of the CO_2 flux module
- Bayesian calibration

2-Evaluation

- Multi-sites test
- Estimation of prediction error with independent data sets

3-Application

- Quantification of CO_2 budgets
- Integration of the various greenhouse fluxes
- Test of mitigation scenarios

1- Introduction

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Biophysical processes underlying greenhouse gas exchanges

Methods to quantify greenhouse gas fluxes

Objectives and modelling approach

2- Modelling and monitoring of greenhouse gas fluxes

The CERES-EGC model

Experimental measurements

Bayesian calibration and model evaluation

3- Results and discussion

Bayesian calibration of the N_2O and CO_2 exchange modules

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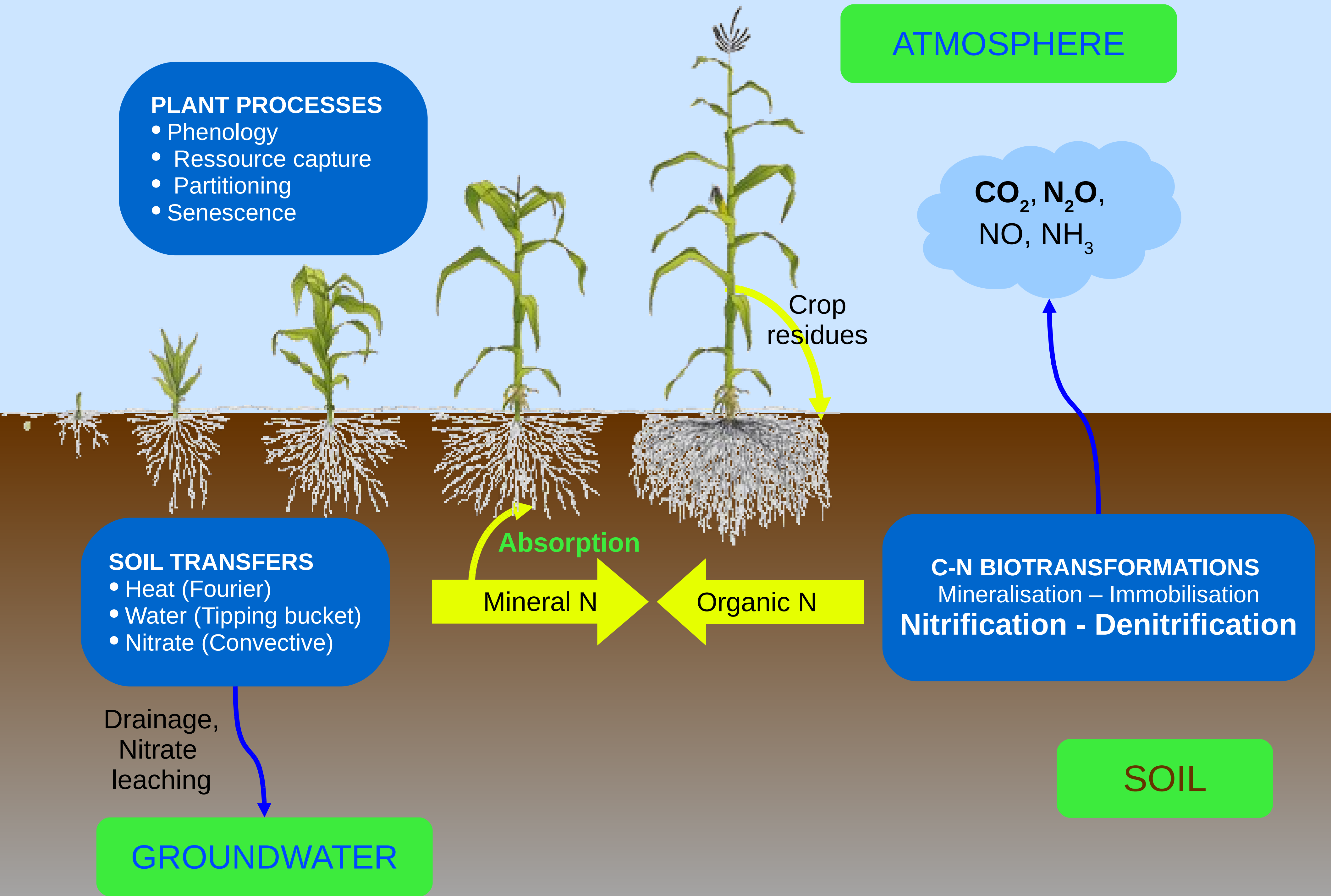
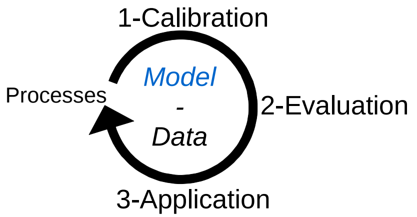
The CERES-EGC model



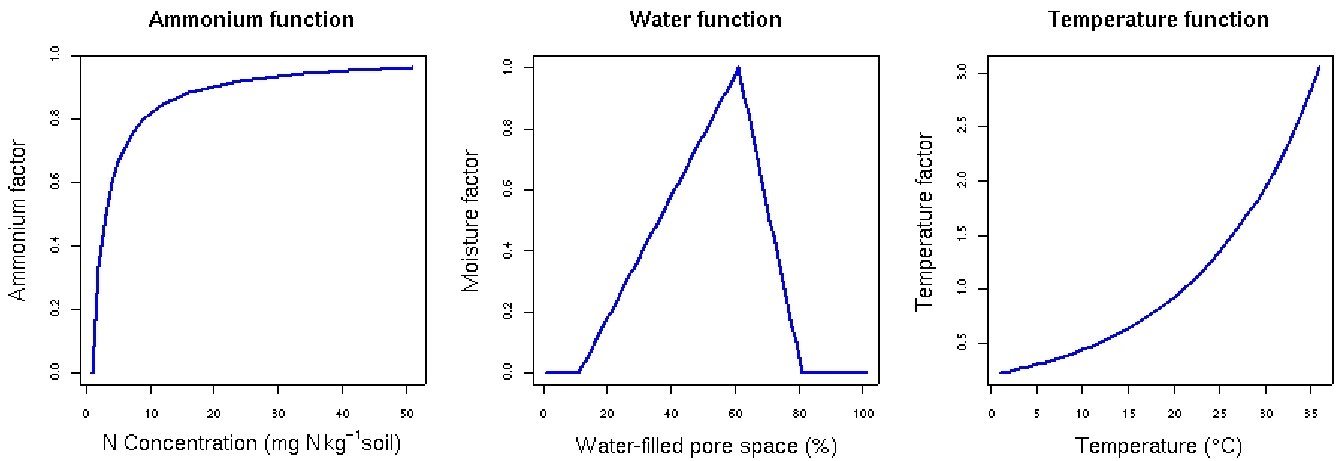
The nitrous oxide module



Nitrification rate (N_i, kg N ha^{-1} d^{-1}) =

MNR x f(WFPS) x f(T)x f(NH4)

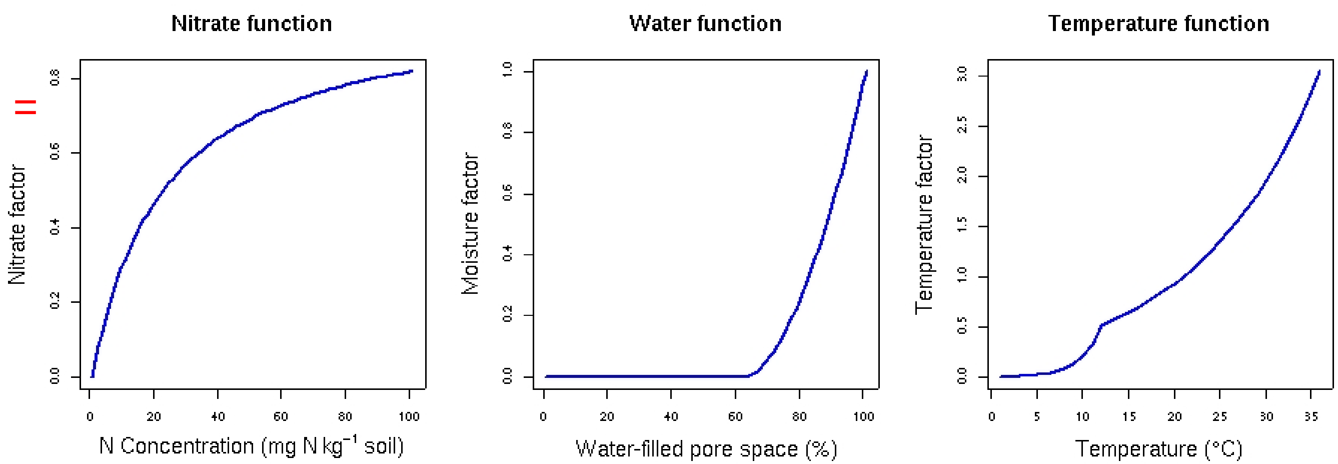
MNR: Maximum Nitrification Rate



Denitrification rate (D_N, kg N ha^{-1} d^{-1}) =

PDR x f(WFPS) x f(T)x f(NO3)

PDR: Potential Denitrification Rate



$$N_2O \text{ emissions} = [r \times Dn] + [c \times Ni]$$

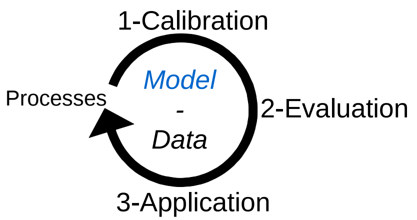
r: Proportion of denitrified N emitted as N_2O

c: Proportion of nitrified N emitted as N_2O

11 “Global” parameters :
Constants in the model equations

4 “Local“ parameters :
Laboratory measurements on soil samples

The carbon dioxide exchanges



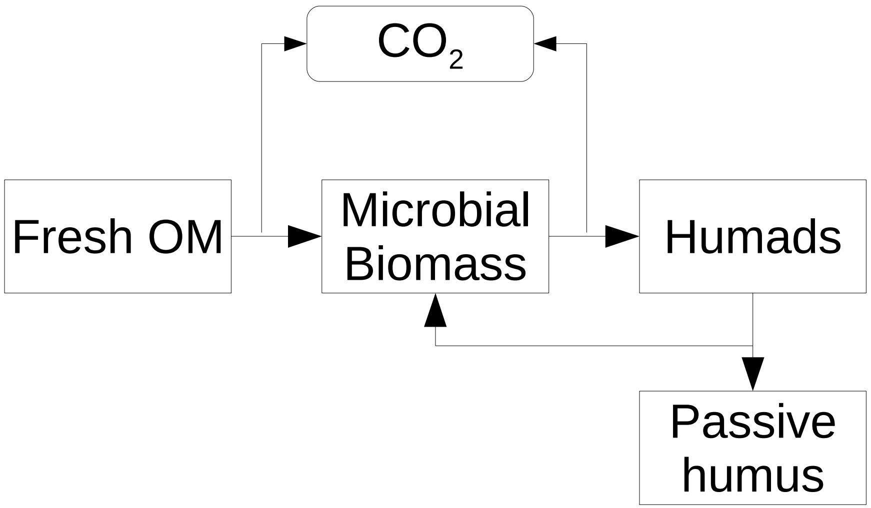
Net primary production (NPP) = RUE x PAR_{aj} x stress coef.

Monteith approach

RUE: radiation use efficiency (g DM MJ^{-1} PAR) ; PAR: photosynthetically active radiation (MJ m^{-2})

Soil respiration (RS) =

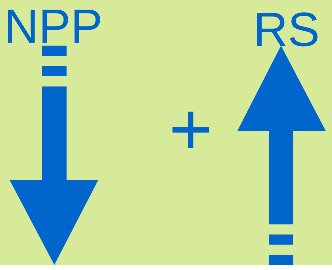
Heterotrophic soil respiration



First-order kinetics :

$$\frac{dC_i}{dt} = -k_i \, C_i \, f_N \, f_T \, f_W$$

Net Ecosystem Production =



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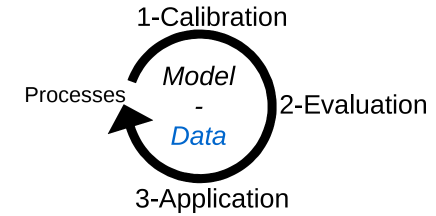
Field experiments



Continuous monitoring of gas and C-N fluxes
of the various ecosystem compartments

PLANTS

- LAI
- Biomass
- CN contents

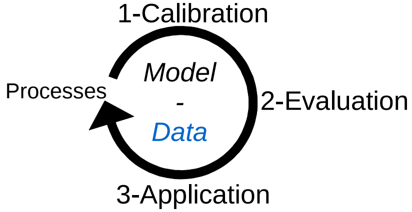
SOIL

- T°, Moisture
- Concentrations NO_3^-, NH_4^+

Exchanges of greenhouse gases

- Manual / Automatic chambers (N_2O, CO_2 ,CH_4)
- Eddy-covariance (CO_2, H_2O)

Experimental design



Main Field NitroEurope, AgroParisTech experimental farm

5 automatic chambers
+ 8 manual chambers

Breakdown of the Maize-Wheat-Barley-Mustard rotation on **3 annex plots**

Plot 1 PAN1	*Plot 2 PAN2*	*Plot 3 PAN3*
2007 : Barley, Mustard 2008 : Maize 2009 : Wheat	2007 : Maize 2008 : Wheat 2009 : Barley	2007 : Wheat 2008 : Barley, Mustard 2009 : Maize

5 manual chambers / plot

+ Soil moisture,
N concentrations,
Crop Dry matter & productivity

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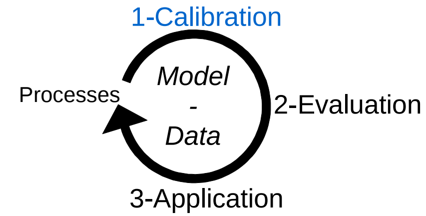
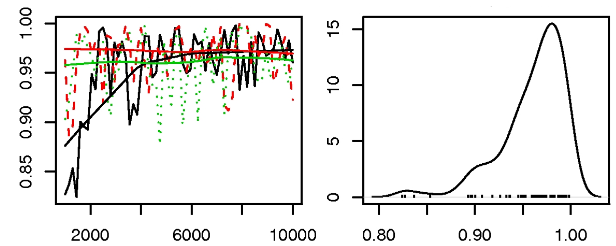
Overview of Bayesian Calibration

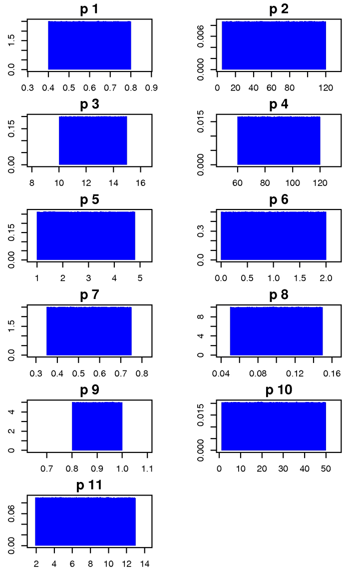


Measurements
(Statistical model to link data to parameters)

Bayesian Calibration

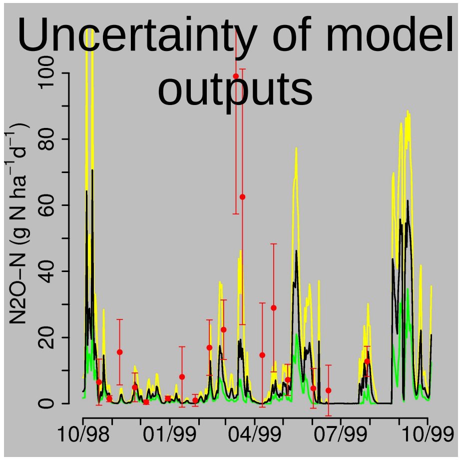


Posterior calibrated distribution for the parameters

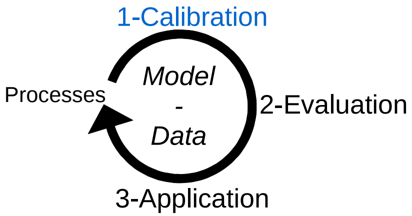


Prior information about parameter distribution

Uncertainty of model outputs



Estimation of model parameters by Bayesian Calibration



- *Parameters (θ)* = constants in model equations

- *Data (D)* = vector of observations

Bayes' theorem
for model parameters

$$P(\theta/D)=\frac{P(D/\theta)P(\theta)}{P(D)}$$

P(θ) = Prior distribution
Prior information about parameters

P(D/θ) = Likelihood function
Function relating data to parameters

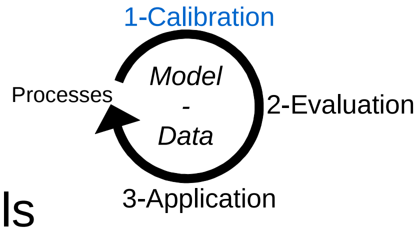
P(θ/D) = Posterior distribution
Synthesis of the 2 sources of information
by a simple multiplication

P(D) = Not explicitly computed.

Thomas Bayes
1701-1761

Likelihood function : $$\log L \propto \sum_{j=1}^{K}\left(\frac{O_j - S_j}{\sigma_j}\right)^2$$

Markov Chains Monte Carlo (MCMC)

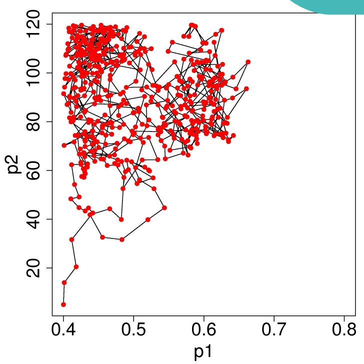


MCMC may be applied to numerical models such as agro-ecosystem models

Data
Prior uncertainty -------> Posterior uncertainty

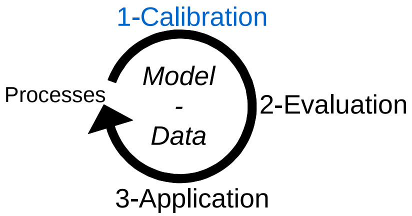
MCMC using the Metropolis-Hastings algorithm:

Random walk through the parameter-space:
Set of visited points approaches
the posterior parameter distribution P(θ/D)



Sample of 10^4-10^5 parameter vectors from the posterior distribution P(θ/D)

Prior information on parameters



N_2O parameters

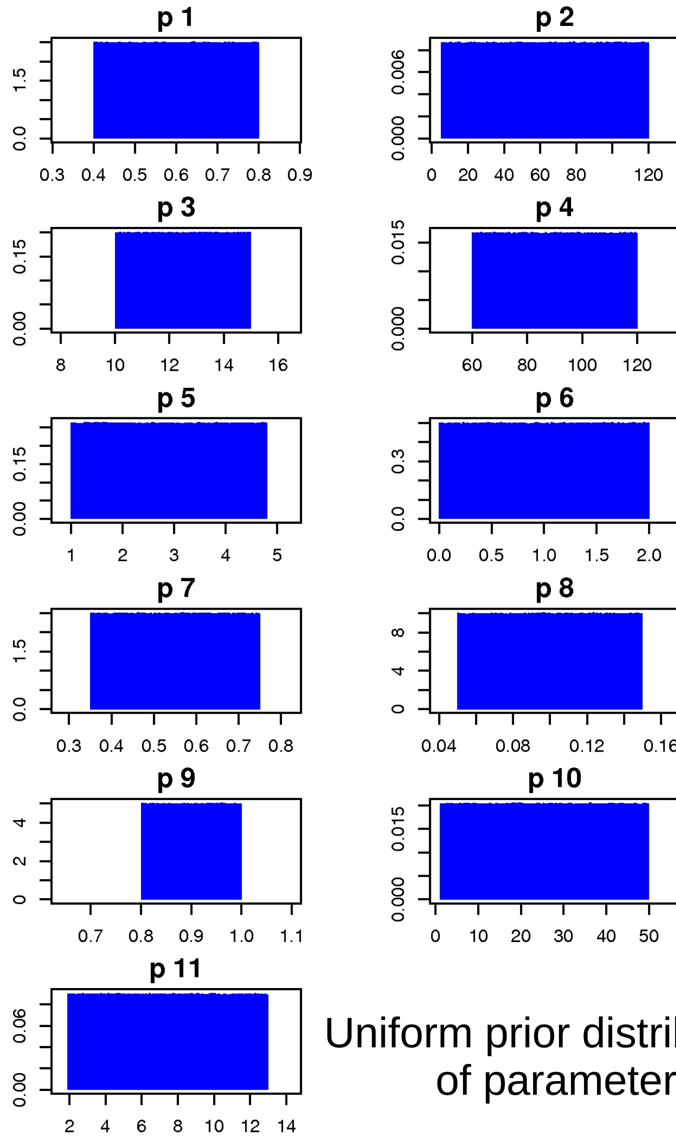
- The 11 global parameters of the nitrification-denitrification response functions.

CO_2 parameters

- 6 parameters related to crop growth (RUE of main crops)

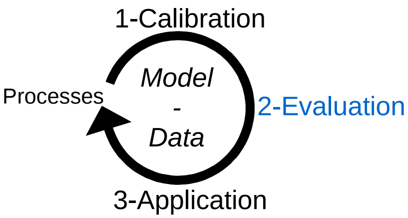
+

- 10 parameters related to SOM turn-over (decomposition rates and partitioning coef. of the different pools)



Uniform prior distributions of parameters

Methods to evaluate the model



- Statistical indicators to assess **the goodness of fit**

Mean deviation : $MD = \frac{1}{n}\sum_{i=1}^{n}(O_i - S_i)$

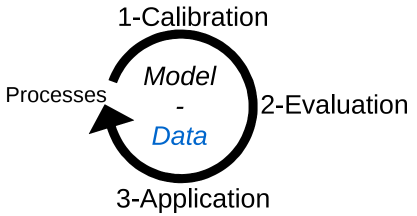
Root mean square error : $RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(O_i - S_i)^2}$

- And to estimate the **prediction error**

Calculation of the "Root Mean Square Error of prediction" (RMSEP ; Wallach, 2006)
With data sets independent of the parameter calibration step.

Data sets for **parameter estimation** $\neq$ Data sets for **model evaluation**

Field sites and treatments



9 sites and 17 datasets of GHG fluxes

Sites	Treatments	Years	Crop types	Soil types
Rafidin	N0	1994-1995	Rapeseed	Rendzina
	N1	1994-1995	Rapeseed	
	N2	1994-1995	Rapeseed	
Villamblain		1998-1999	Wheat	Loamy Clay
La Saussaye		1998-1999	Wheat	Clay Loam
Arrou		1998-1999	Wheat	Loamy Clay
Champ Noël	CT	2002-2003	Maize	Silt Loam
	AN	2002-2003	Maize	
Le Rheu	CT	2004-2005	Maize	Silt Loam
	AN	2004-2005	Maize	
Grignon	NEU	2004-2008	M-WW-B-m	Silt Loam
	PAN1	*2007-2008*	*Maize*	
	PAN2	*2007-2008*	*Wheat*	
	PAN3	*2007-2008*	*Barley*	
	BPA	*2002*	*Maize*	
Auradé		2005-2007	R-WW-SF	Clay Loam
Gebesee		*2006-2007*	*SB-WW*	*Silty Clay-Loam*

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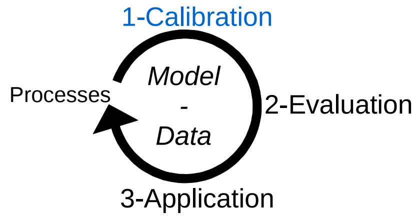
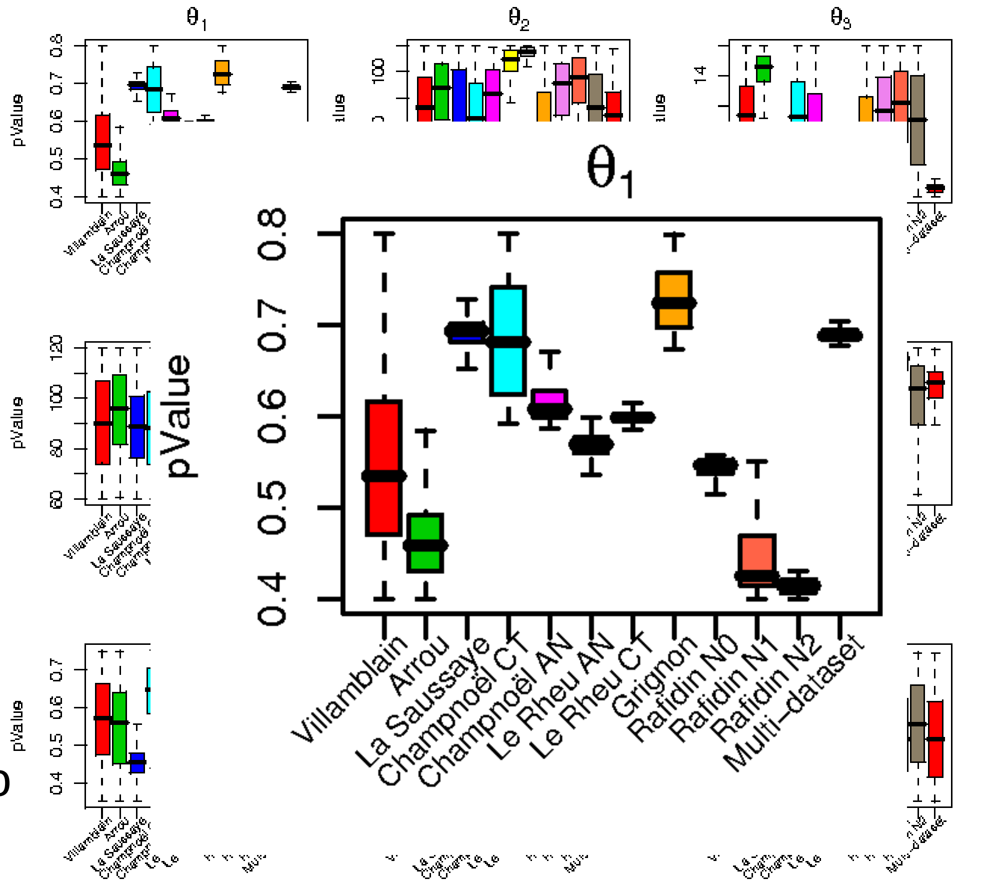
Bayesian calibration of the N_2O emission module

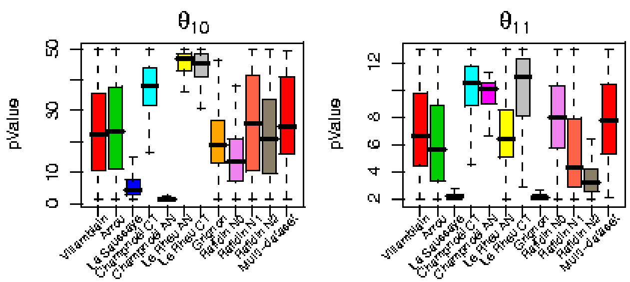


Step 1 : To calibrate the global parameters against each data set

Comparison of posterior parameter distributions

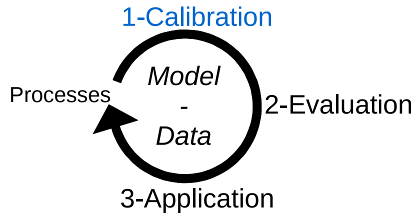
- With data from manual chambers measurements (15-25 measurements per yr) for 11 data sets.
- The posterior distributions are narrower than the prior distributions (uniform).
- The differences across sites make it impossible to identify generic values for global parameters.





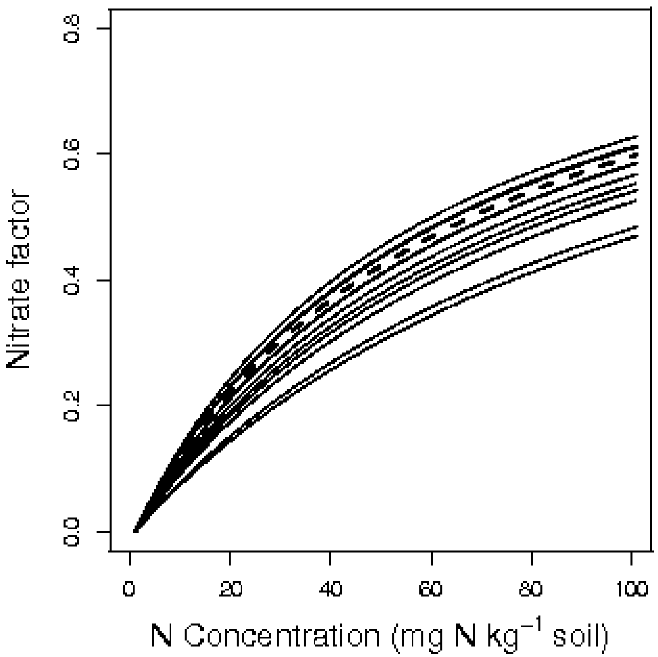
Θ1	WFPS threshold
Θ2	Half-saturation constant (denit)
Θ3	Temperature threshold
Θ4	Q10 factor for low temperatures
Θ5	Q10 factor for higher temperatures
Θ6	Exponent of power function
Θ7	Optimum WFPS for nitrification
Θ8	Minimum WFPS for nitrification
Θ9	Maximum WFPS for nitrification
Θ10	Half-saturation constant (denit)
Θ11	Q10 factor for nitrif.

Bayesian calibration of the N_2O emission module

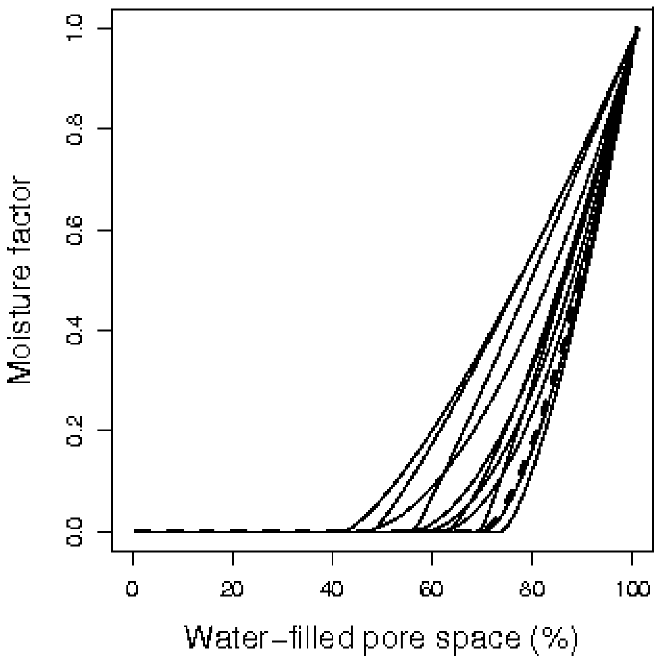


Step 1 : To calibrate the global parameters against each data set

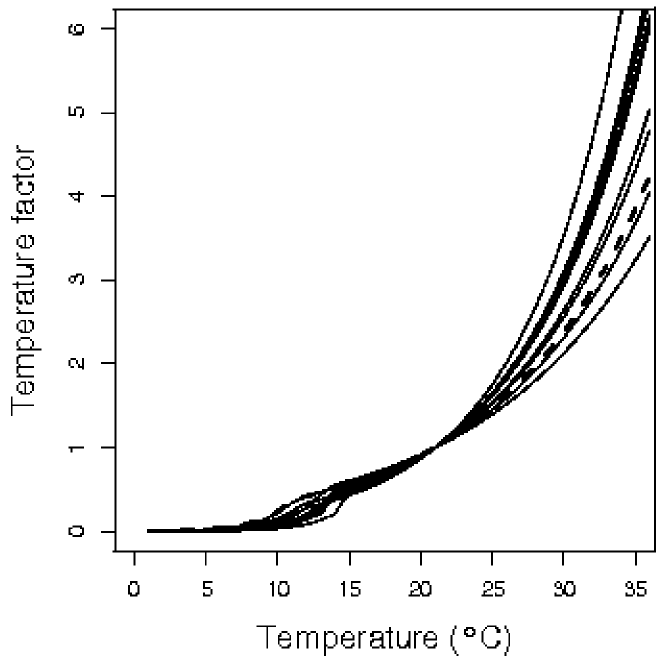
Nitrate function (f_N)



Water function (f_W)

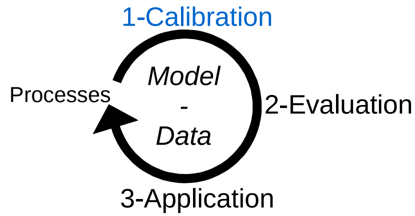


Temperature function (f_T)



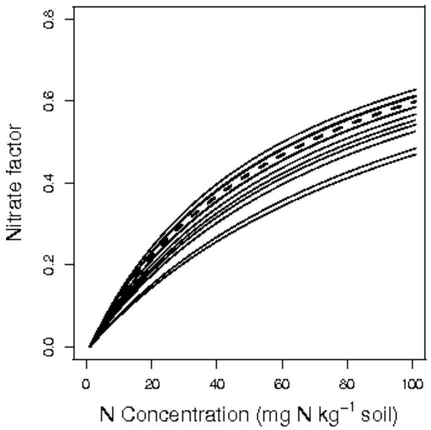
- The response functions of nitrification and denitrification were optimised for each site.

Bayesian calibration of the N_2O emission module

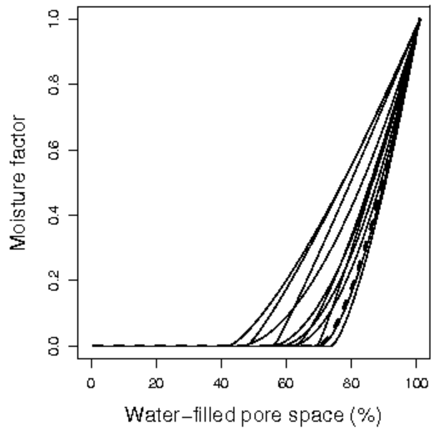


Step 1 : To calibrate the global parameters against each data set

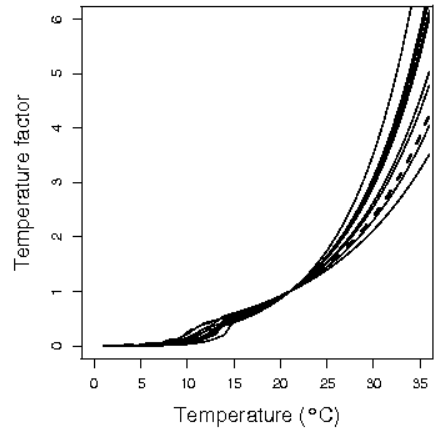
Nitrate function (f_N)

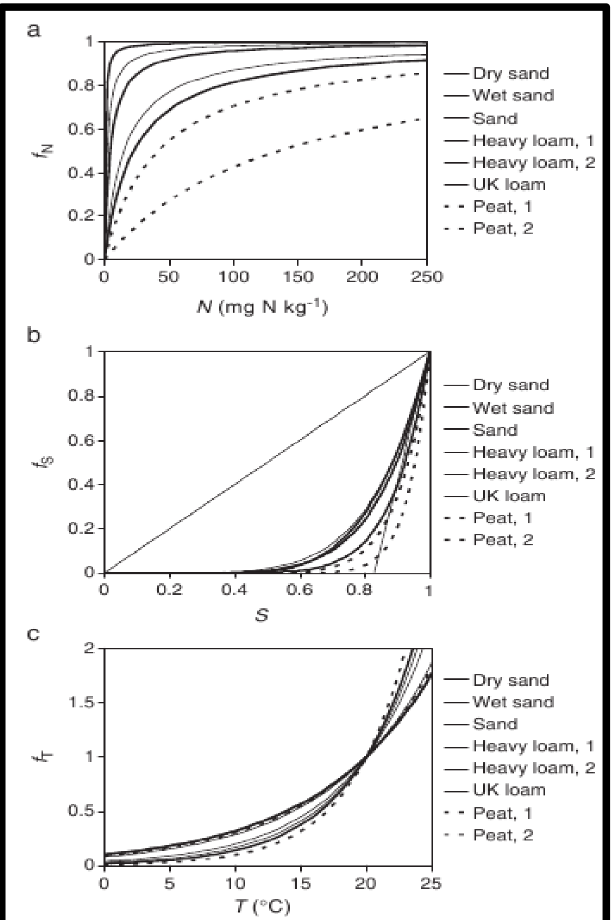


Water function (f_W)



Temperature function (f_T)

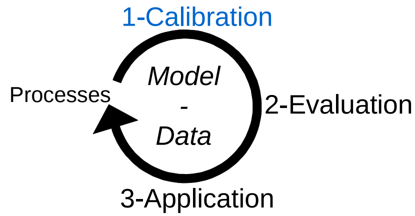




Heinen M., 2006. Application of a widely used denitrification model to Dutch data sets. Geoderma 133, 464-473.

- Heinen (2006) suggested the impossibility of defining a set of response functions for denitrification that would be applicable to different soil types.

Bayesian calibration of the N_2O emission module



Step 2 : To obtain universal estimates for the global parameters

"Multi-sites" procedure : $p(\theta|Y_1,\ldots,Y_{11}) \propto p(Y_1,\ldots,Y_{11}|\theta)\,p(\theta)$

The global parameters were calibrated by running the Bayesian calibration procedure with the 11 data sets simultaneously.

The model can be applied for new sites or for model extrapolation by using the subset of response functions obtained with the **"multi-sites" calibration**.

RMSE with the "site-by-site" procedure

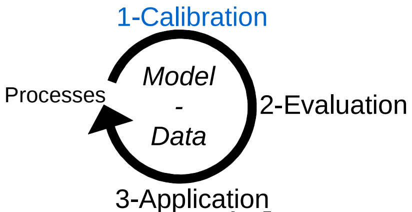
improved by 75 % on average in comparison with prior predictions

RMSE with the "multi-sites" procedure

improved by 33% on average in comparison with prior predictions

Lehuger et al., 2009. Bayesian calibration of the nitrous oxide emission module of an agro-ecosystem model. Agr. Ecosys. Env. (In press).

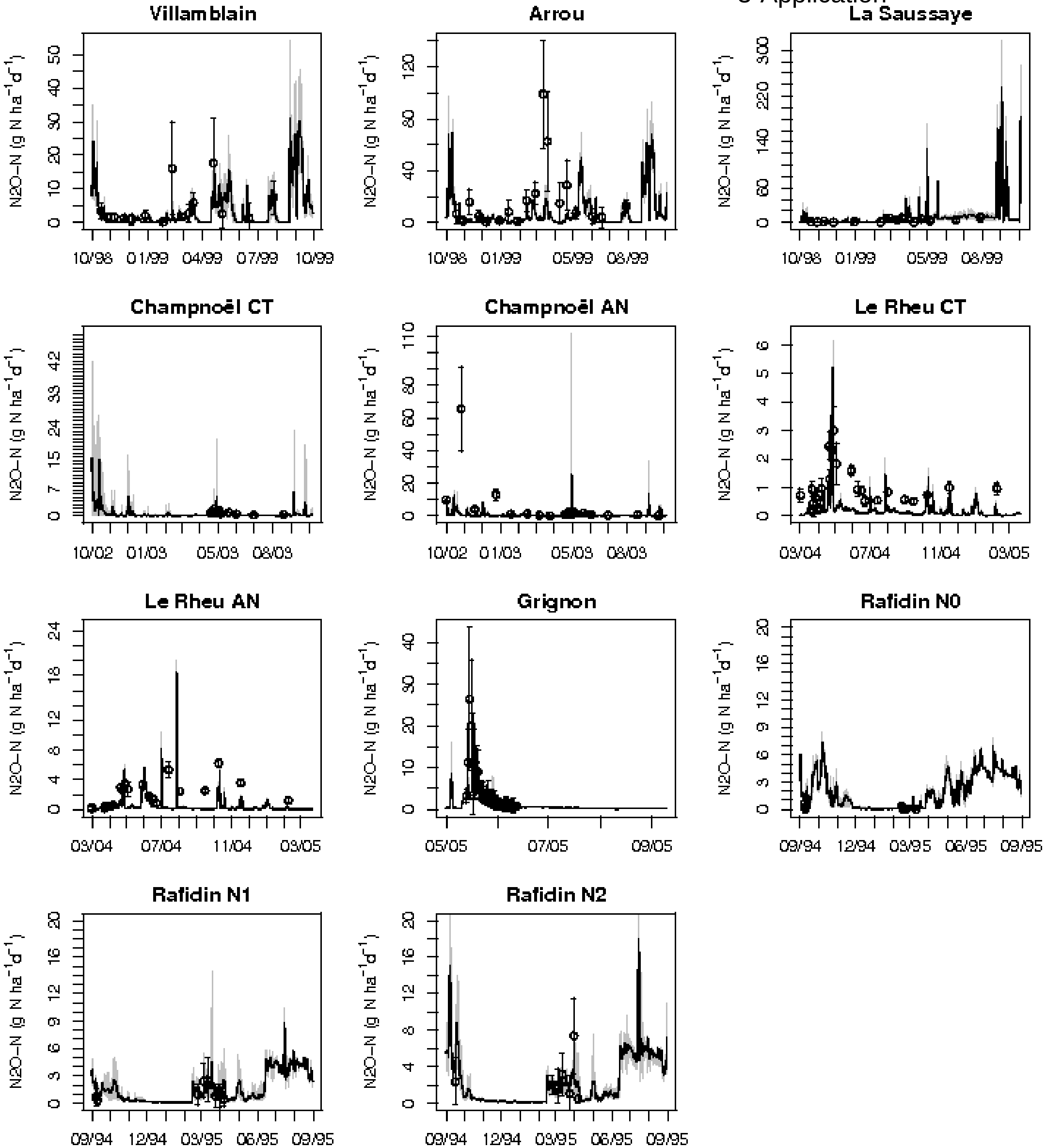
Bayesian calibration of the N_2O emission module



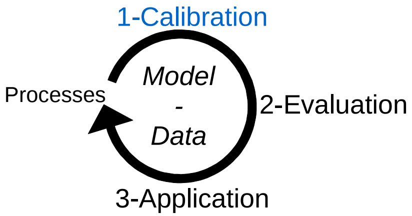
Posterior simulations of the N_2O emissions for the 11 experimental data sets.

- Sites generally have low emissions and occasional peaks with large spatial variability.

- The under-estimation of emissions peaks is due to the lower weight of the fluxes with high variance in the calculation of the likelihood function.



Bayesian calibration of the N_2O emission module



Step 3 : To estimate the 6 most sensitive parameters including the local parameters

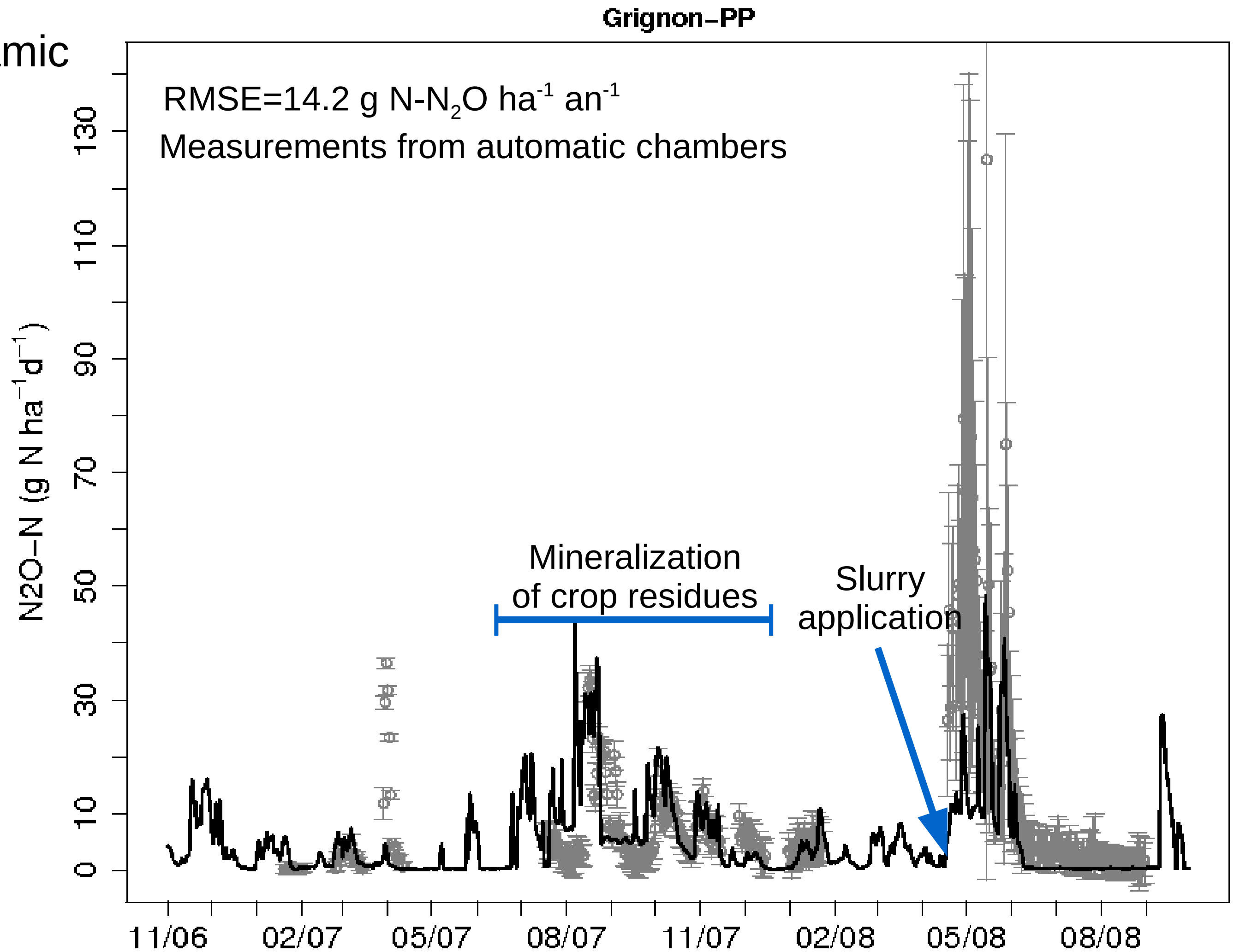
1- Selection of a parameter subset

(Lamboni et al., 2009. Multivariate global sensitivity analysis for dynamic crop models)

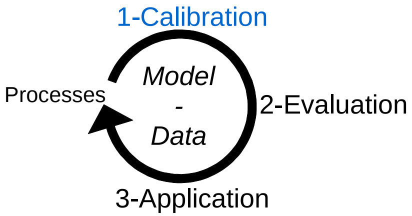
2- Bayesian calibration

A posteriori simulations of N_2O emissions for the Grignon arable site

- Good estimates during mineralization of crop residues
- Difficulty to simulate the N_2O peak consecutive to slurry application



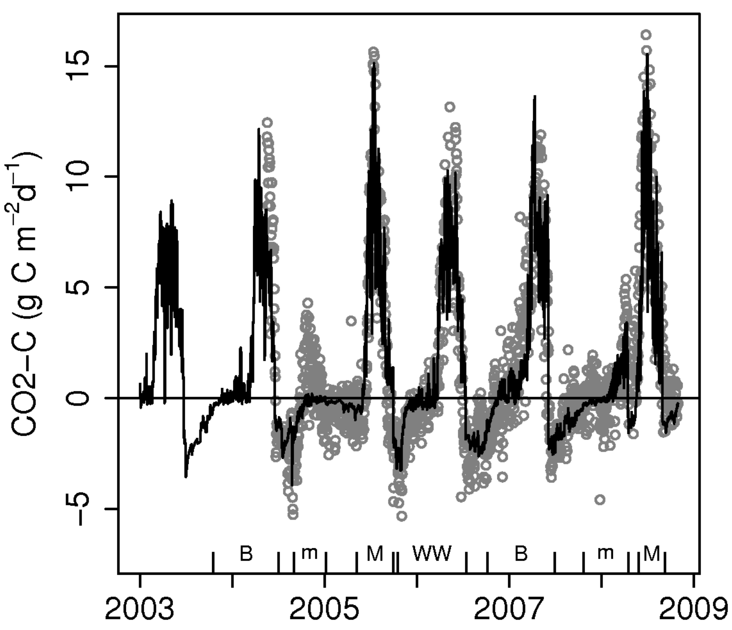
Bayesian calibration of the CO_2 exchange module

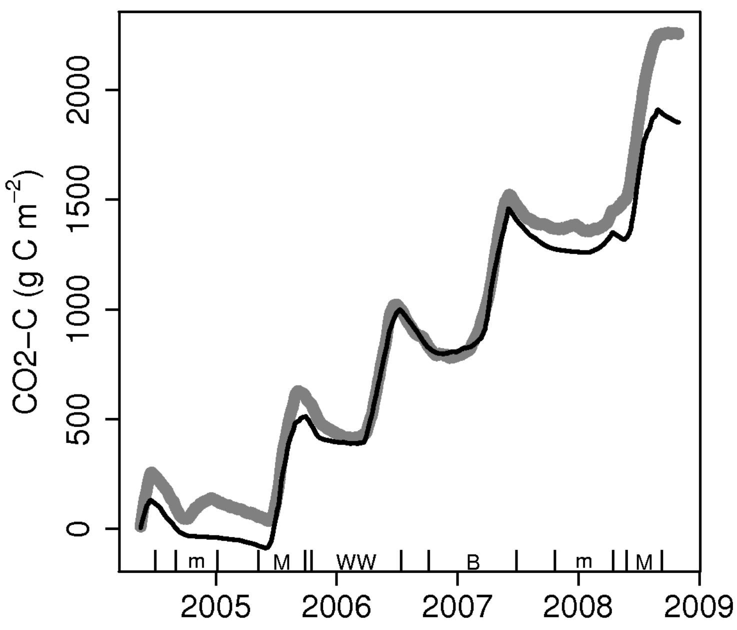


A posteriori simulations of net CO_2 fluxes

- Good estimation of NEP from daily to entire crop rotation scale
- Model performance was improved by 15-30 % in comparison with default parameter values
- C fluxes can be estimated during the growing season and the period between 2 crops (catch crop, volunteers)

Grignon
(RMSE = 1.90 g C m^{-2} d^{-1}, n=1627)





The model can quantify the C balance of crop rotations

Lehuger et al., 2009. Predicting the net carbon exchanges of crop rotations in Europe with an agro-ecosystem model. Agr. Ecosys. Env. (In submission).

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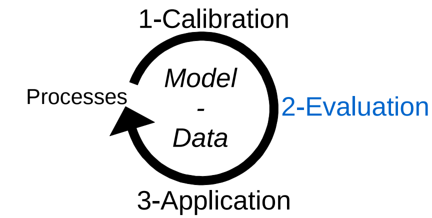
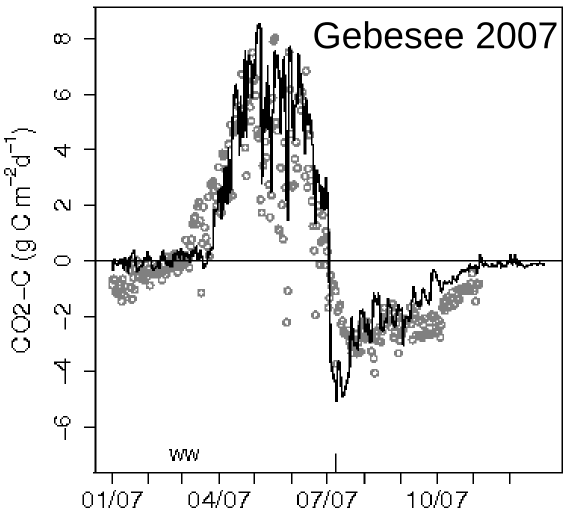
Model evaluation



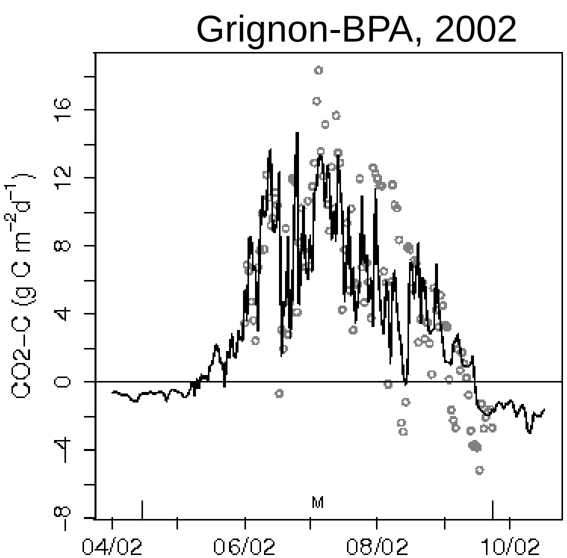
Net ecosystem exchanges

(g C m^{-2} d^{-1})

Wheat

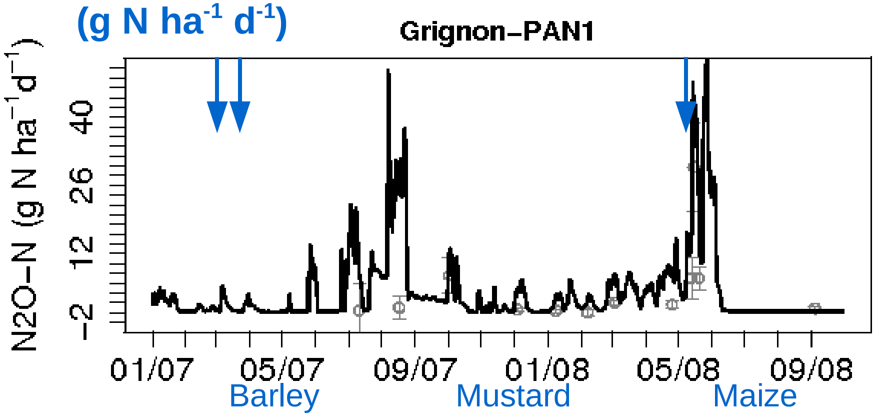


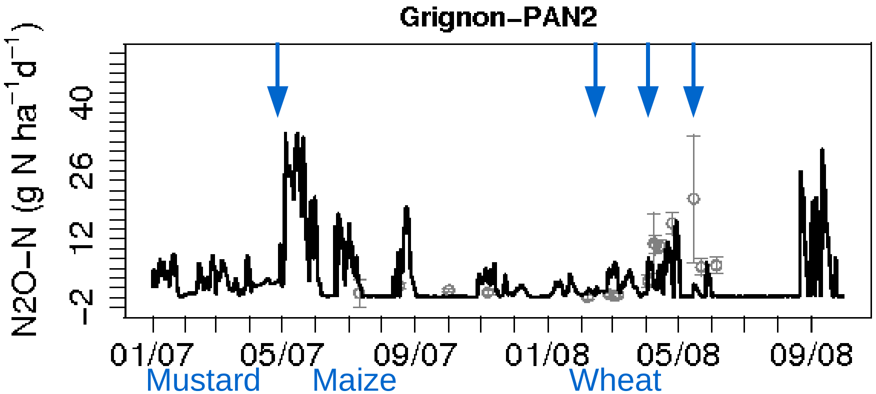
Maize

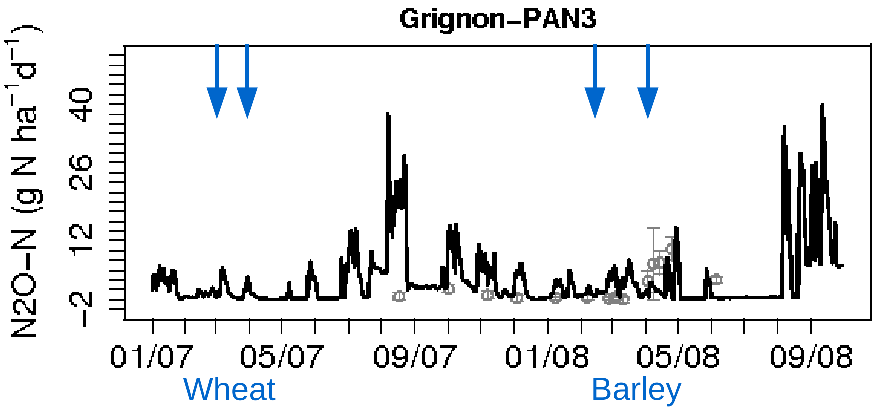


N_2O emissions

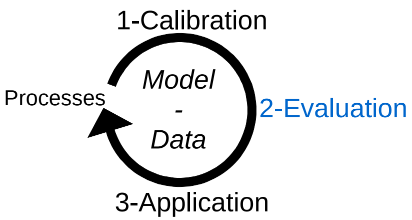
(g N ha^{-1} d^{-1})







Model evaluation



Evaluation of prediction errors
with independent data sets

N_2O

- Error of prediction comparable or lower than those of other agro-ecosystem models :

DNDC (*Beheydt et al, 2007) : 340 g N-N_2O ha^{-1} d^{-1} ; Maize*
196 g N-N_2O ha^{-1} d^{-1} ; Beans-Beets

N_2O	RMSEP (g N-N_2O ha^{-1} j^{-1})
Grignon-PAN1	9,6
Grignon-PAN2	7
Grignon-PAN3	7,3
Gebesee	4,6

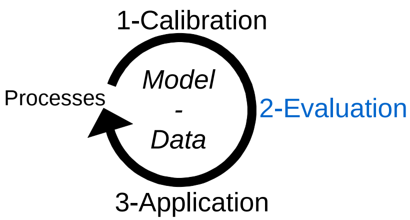
CO_2

- Error of prediction lower than those of other agro-ecosystem models at the daily scale :

Agro-C *(Huang et al., 2009) : 11.3 g C-CO_2 m^{-2} d^{-1}*
for a wheat-maize sequence

CO_2	RMSEP (g C-CO_2 m^{-2} j^{-1})
Grignon-BPA	3,78
Gebesee	1,55

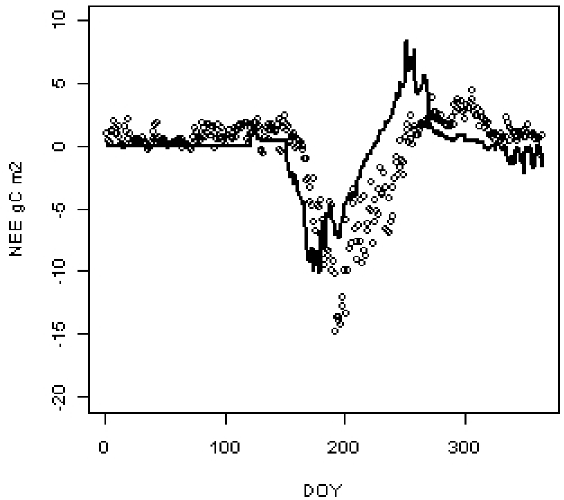
Model evaluation



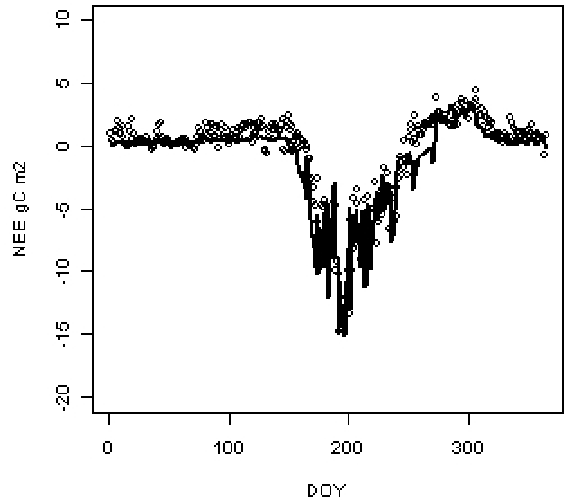
Inter-comparison of models for CO_2 simulations (NEE)

Maize 2005 Grignon (First results)

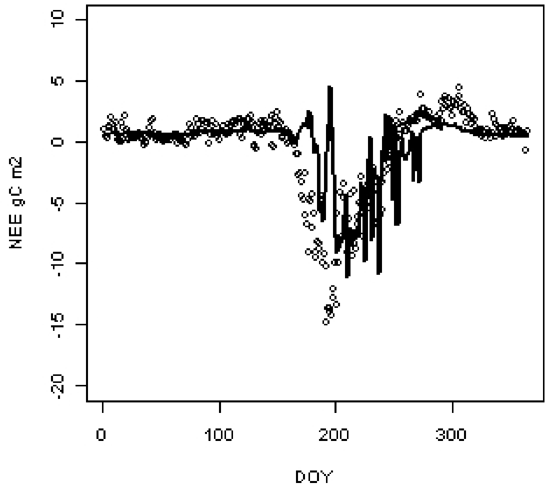
DNDC



CERES-EGC after calibration



Orchidée-Stics



M. Wattenbach, N. Vuichard, S. Lehuger et al.
The carbon balance of European croplands: a trans-European, cross-site, multi model simulation study. (In preparation for AGEE)

The Bayesian calibration improves the goodness of fit in comparison with uncalibrated models

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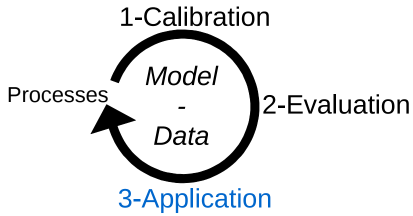
Emission factors for N_2O



Annual fluxes and emission factors for N_2O

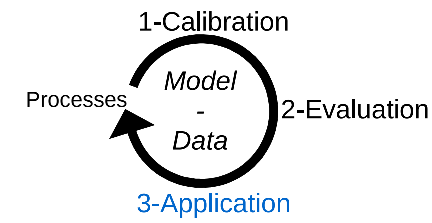
Model

Site	Treatment	N_2O fluxes ($g\ N\ ha^{-1}\ y^{-1}$)	0.05 quantile ($g\ N\ ha^{-1}\ y^{-1}$)	0.95 quantile ($g\ N\ ha^{-1}\ y^{-1}$)	IPCC ($g\ N\ ha^{-1}\ y^{-1}$)	Emission factor (%)
Rafidin	N0	689	578	741	0	-
	N1	584	473	824	1550	0.07 (0.00-0.22)
	N2	819	629	1183	2620	0.10 (0.03-0.24)
Villamblain		1465	454	2989	2300	0.36 (0.00-1.02)
Arrou		3672	1676	5874	1800	0.26 (0.00-1.49)
La Saussaye		3215	572	6035	2000	1.12 (0.00-2.53)
Champnoël	CT	218	49	746	0	-
	AN	336	106	855	1100	0.06 (0.00-0.53)
Le Rheu	CT	88	66	115	180	-
	AN	183	146	220	1800	0.05 (0.03-0.08)
Grignon		150	143	163	1400	0.05 (0.04-0.05)

Posterior estimation **Uncertainty**

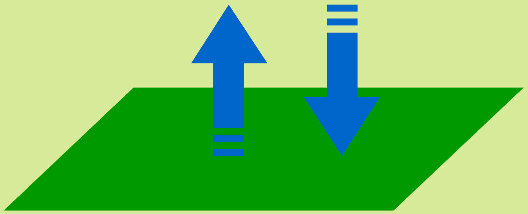
Emission factors vary across sites. Range: 0.05 – 1.12 %

Estimating the global warming potential of cropping systems



Direct emissions

CO_2 N_2O CH_4

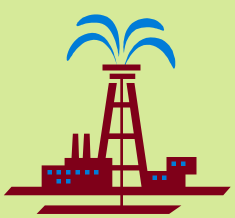


- **CO_2** and **N_2O**: from model simulations over ~30 years.

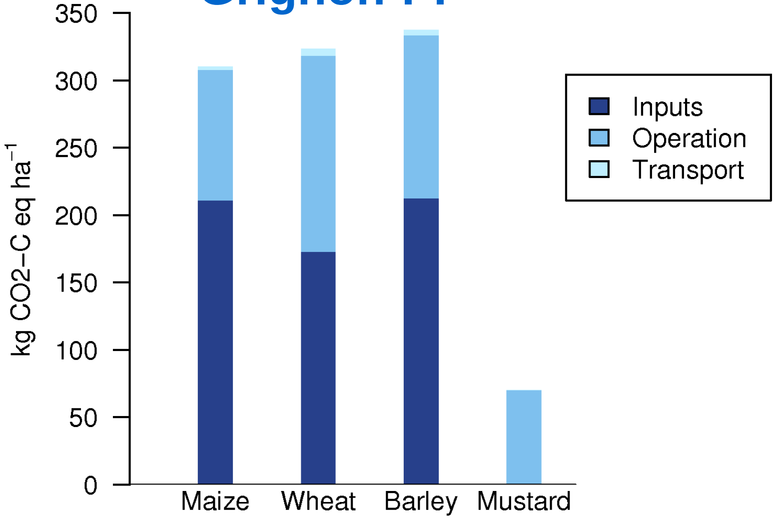
NBP = NEP – Exported biomass + Imported biomass

- **CH_4**: from field-measurements

Indirect emissions (upstream)

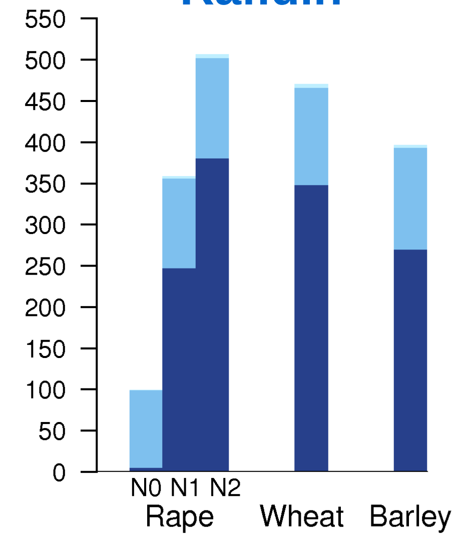


Grignon-PP



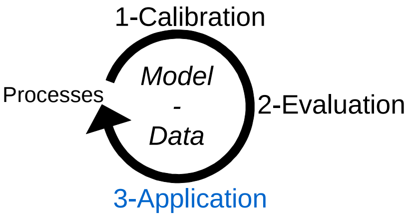
350 kg CO_2-C eq ha^{-1} yr^{-1}

Rafidin



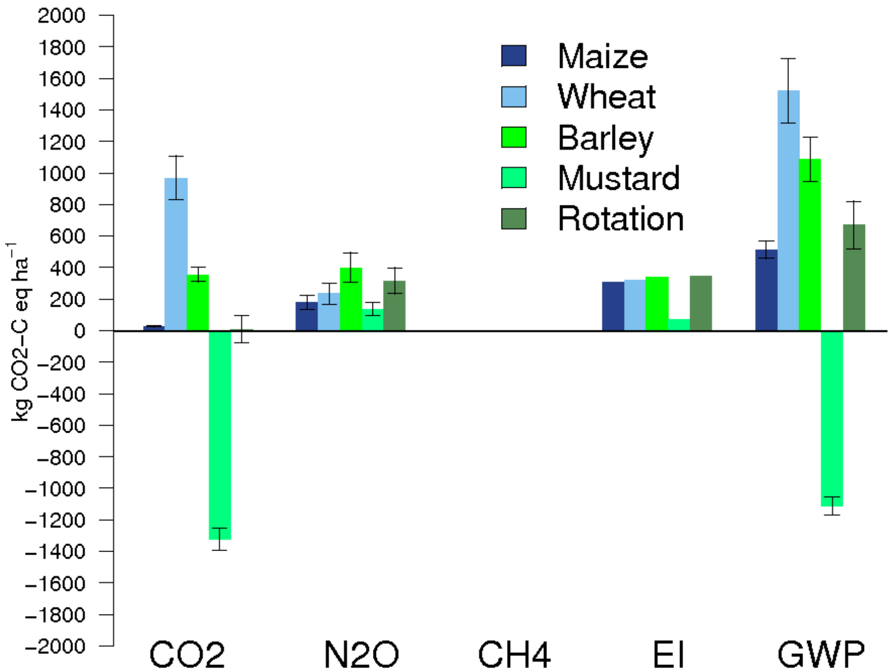
320 - 460 kg CO_2-C eq ha^{-1} yr^{-1}

Estimation of global warming potential of cropping systems



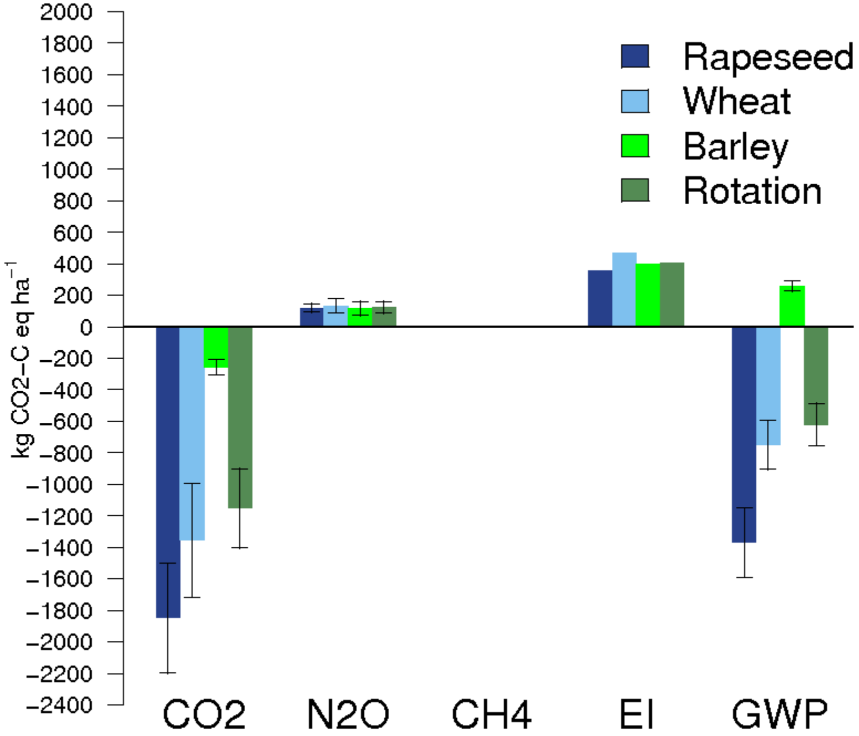
Grignon site

+670 kg CO2-C eq ha-1 yr-1



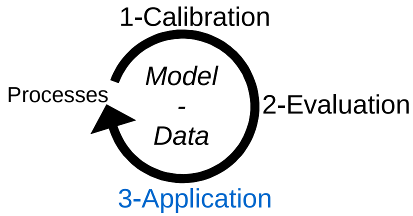
Rafidin site

-650 kg CO2-C eq ha-1 yr-1

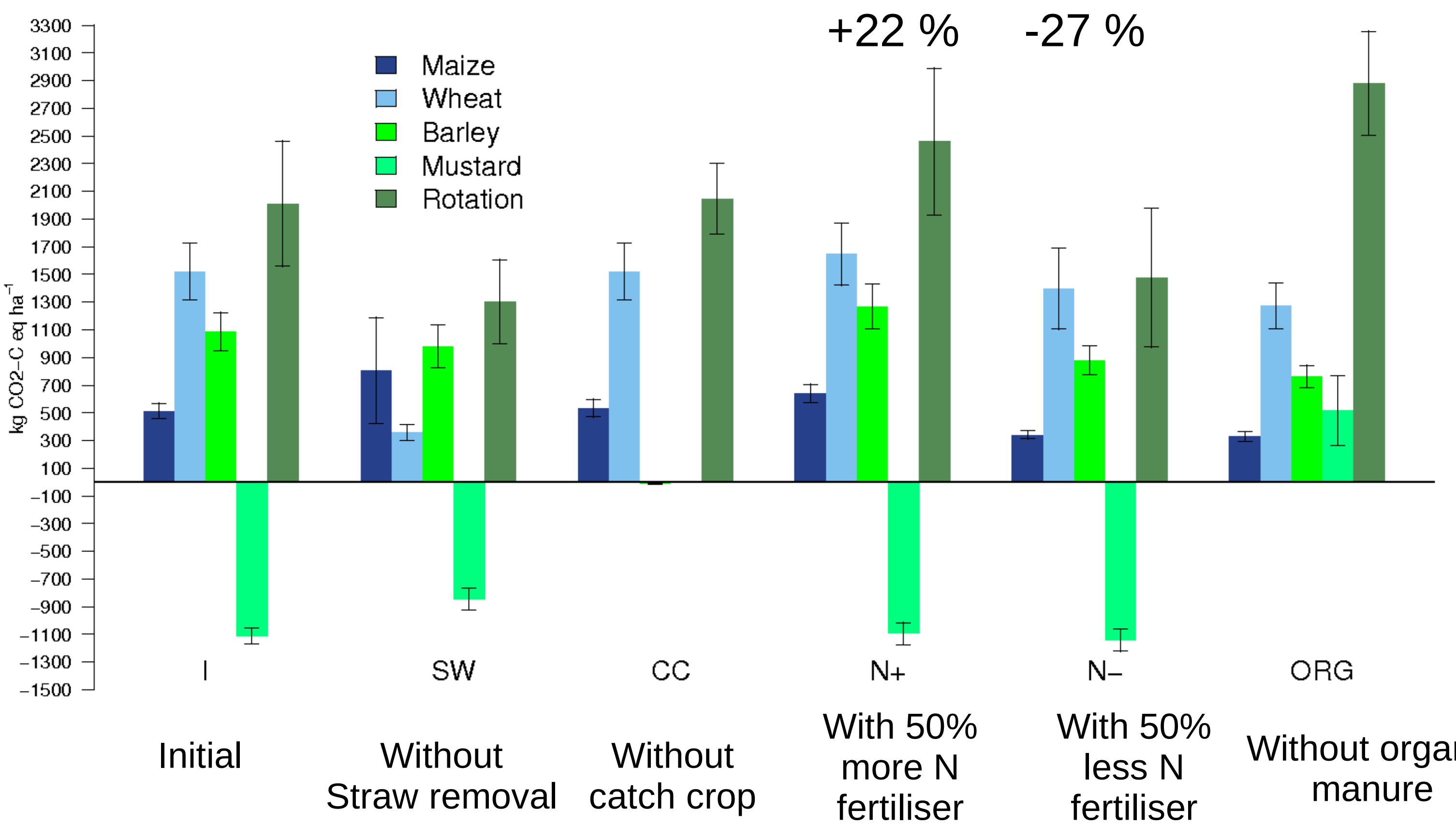


The main differences between both sites comes from the CO_2 term

Reducing impact of crop production on global warming at the plot-scale



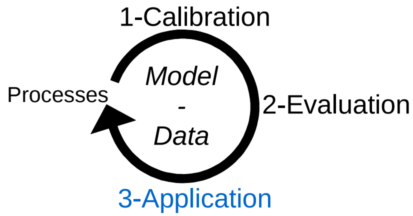
Tests of mitigation scenarios for a maize-wheat-barley-mustard crop sequence



GWP per t DM exported (grain yield + maize silage): **67** **42** **68** **80** **52** **98**

C and N management may help in designing cropping systems with low global warming potential

Reducing impact of crop production on global warming at the plot-scale

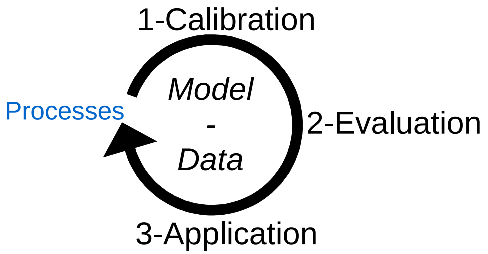


Efficiency of mitigation options:

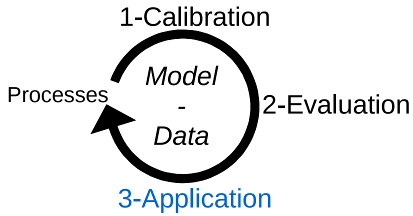
- Using cover (catch) crop to enhance C sequestration
- Determination of the C returns necessary to offset the other greenhouse gas emissions (manure, crop residues)
- N management to find the lowest GWP per ton of product (dose, date and type)

Model improvements

- Technologies (inhibitors of nitrification, biochar...)
- Effect of cropping practices on greenhouse gas fluxes
- Modelling of methane fluxes
- Effect of C quantity and quality on N_2O emissions



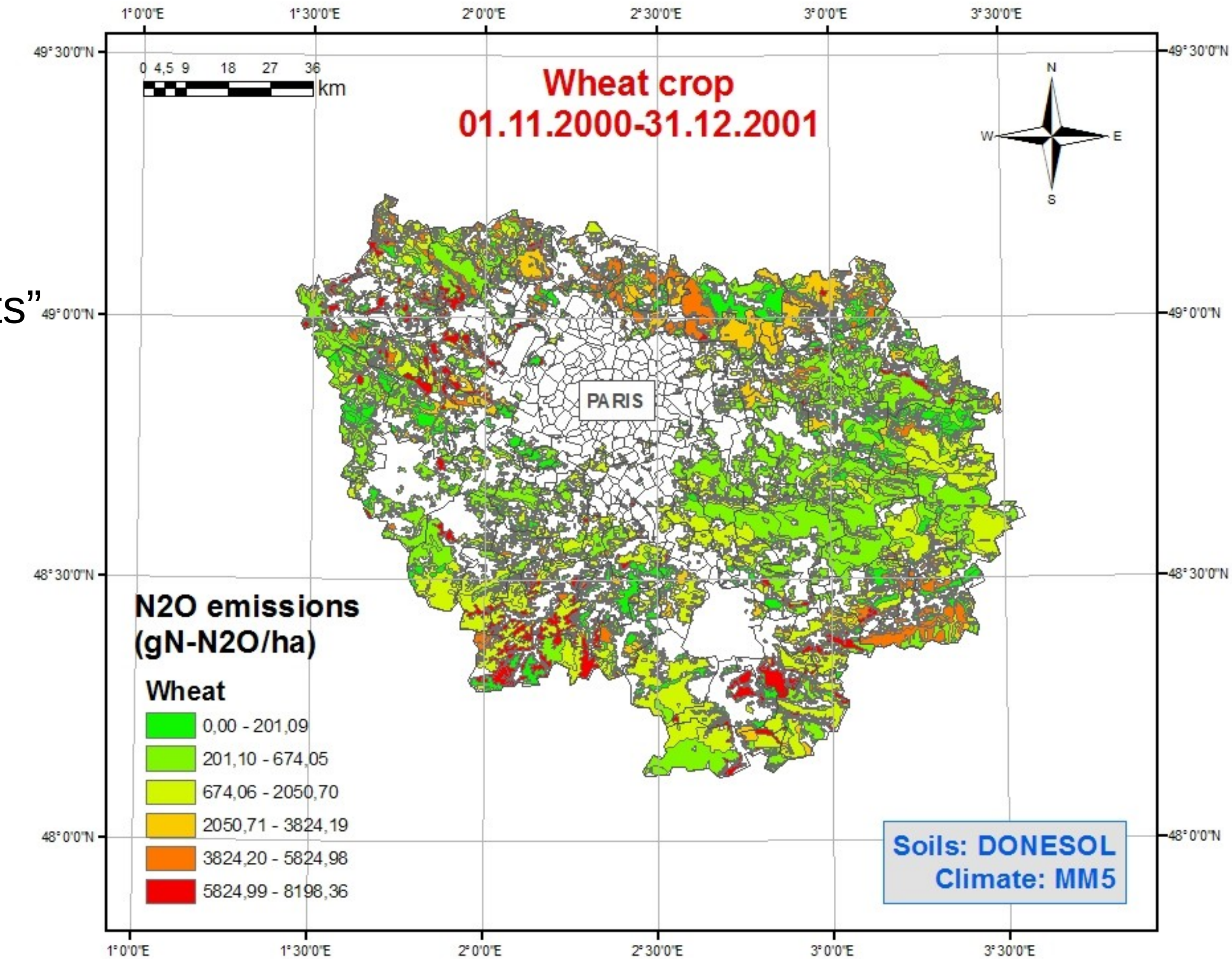
Reducing the impact of crop production on global warming at the regional scale



Model extrapolation at the regional scale

- Spatialized inventories make possible to locate the “hot-spots” of N_2O emissions

- Reduction of N_2O emissions more efficient



Inventory of N_2O emissions for the Île-de-France region (12 000 km² – Chaumartin et al., 2009)

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4- Conclusion

Main objective :
To model the exchanges of N_2O and CO_2 at the field-scale
to predict the global warming potential of agro-ecosystems

Model improvement to simulate the CO_2 and N_2O fluxes

- Application and development of an original Bayesian calibration method.
- Evaluation of model prediction error with independent data.

Model application

- Estimation of global warming potential.
- Test of mitigation scenarios.

Methodological developments

- Generic method to estimate the greenhouse gas budget of cropping systems.
- Methodological development for spatial extrapolation based on a procedure of Multi-site Bayesian calibration.
- Methodology for Sensitivity analysis → Bayesian calibration → Uncertainty quantification.

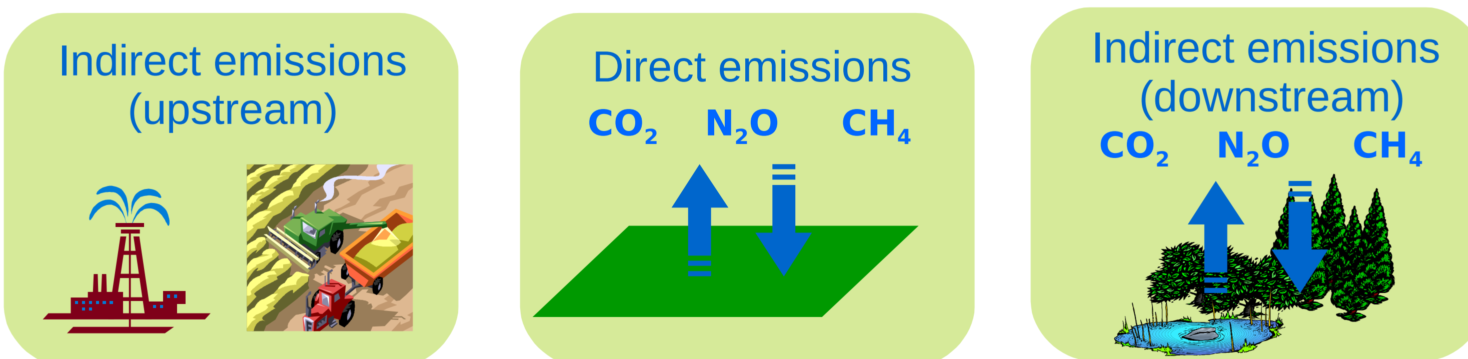
Perspectives (1/2)

✫ Plot-scale modelling

- To improve model structure : model inter-comparison
- To include missing processes : methane fluxes, gas diffusion in soil...

✫ Improving environmental assessment

- To increase the system boundaries : downstream indirect emissions



- Necessity to include additional emissions and depositions of N fluxes (NO_3^-, NO_x, NH_3)
- Development of Landscape models (NitroScape) and Multi-ecosystem models (Mobile)
- Multi-impacts evaluation : eutrophisation, acidification, photochemical oxidation.

Perspectives (2/2)

Predicting greenhouse gas fluxes from agricultural soils at regional (continental) scale

- Dealing with variability of parameters over space : Hierarchical Bayes calibration
- Developing a “bottom-up” approach to estimate inventories of greenhouse gas fluxes
- Evaluating the emission maps against integrative atmospheric measurements (tower fluxes)
- Coupling ecosystem models with atmospheric chemistry-transport models

Merci!

- Benoît Gabrielle (directeur de thèse)
- Mes collègues de l'Équipe Bioatm et de l'Unité EGC
- Yagadeesh Yeluripati, Martin Wattenbach, Marcel van Oijen, Christian Werner, Pierluigi Calanca, Klaus Butterbach-Bahl (NitroEurope C3 , BC-BMC User group)
- Catherine Hénault, David Makowski, Pierre-Alain Jayet, Nicolas Viovy et Pierre Cellier (comité de pilotage)
- Matiyiendu Lamboni
- NitroEurope (financeur)

Merci de votre attention!