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SSS1.2 Element cycling and ecological functions of paddy and wetland soils
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Effect of water and heat transport processes on methane emissions from paddy soils: a process-based model analysis

Anacleto Rizzo
Fulvio Boano
Roberto Revelli
Luca Ridolfi

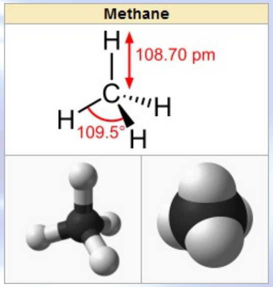
Politecnico di Torino, Turin (Italy)
DIATI -Department of Environment, Land and Infrastructure Engineering

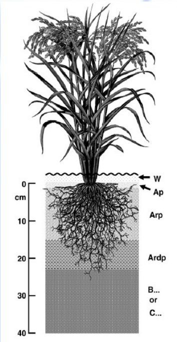
Why the study of CH_4 emissions from paddy?

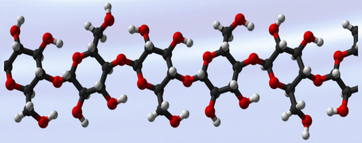
- ***CH_4 potent GHG → high CH_4 emissions from paddy → global warming***
  - 9-19% global CH_4 emissions
  - 15-26% anthropogenic CH_4 emissions

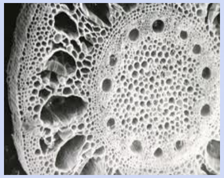
- ***Socio-economic role of rice food***
  - staple food for Asian population
  - (North-)Italy is first rice producer in Europe

- ***Speculative - multidisciplinarity***
  - Eco-Physiology
  - Pedology
  - Biogeochimistry
  - Hydrology
  - Agronomy
  - Engineering



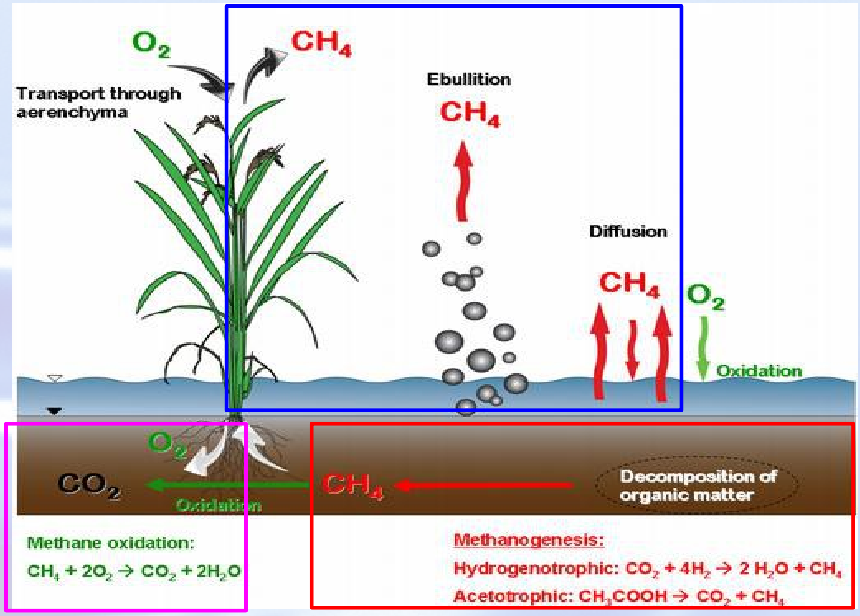


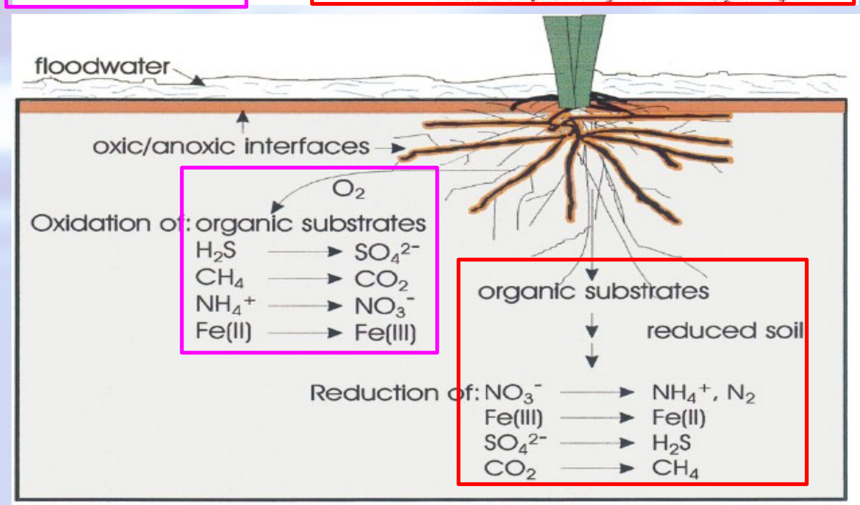




CH_4 dynamics in paddy soil

- **CH_4 production**
  - Microbial decomposition of dissolved organic matter (energy source) in anaerobic conditions due to flooding irrigation
  - Microbial competition: CH_4 is produced after that more energetically favourable electron acceptors (e.g. Fe(III)) are reduced
- **CH_4 oxidation**
  - Atmospheric O_2 released from roots through aerenchyma
  - CH_4 oxidation 10 – 50 % CH_4 produced
- **CH_4 emission**
  - Plant mediated (aerenchyma) (≈ 90%)
  - Ebullition (≈ 8%)
  - Diffusion (≈ 2%)





Process-based model approach to investigate the effect on CH_4 emissions of:

- ***Water transport process***
  - current process-based models neglect or oversimplify water flow effects
- ***Heat transport process***
  - CH_4 production strongly influenced by temperature variations
  - Lowering ponding water temperature (LPWT) within the optimal range of rice plant development → alternative and low-cost CH_4 mitigation strategy
  - LPWT feasibility?
    - Irrigating with slightly colder water
    - Increasing ponding water depth

Model framework

- Monodimensional along vertical depth
- 4 distinct and dependent modules

Hydraulic model

Root model

Biogeochemical model

Temperature model

→ Numerical resolution of partial differential equation (PDE) system

↓

Simulate vertical-temporal dynamics of chemical compounds in paddy soil

↓

CH_4 emissions = f (physics,biogeochemistry,physiology)

→ **Water transport**
Heat transport

Hydraulic model

- ***Muddy layer***

  saturated + roots → Eq. Darcy + S_r $\quad \dfrac{\partial}{\partial z}\left(-K_{1,sat}\dfrac{\partial \Phi_1}{\partial z}\right)=S_r$

- ***Hard pan layer***

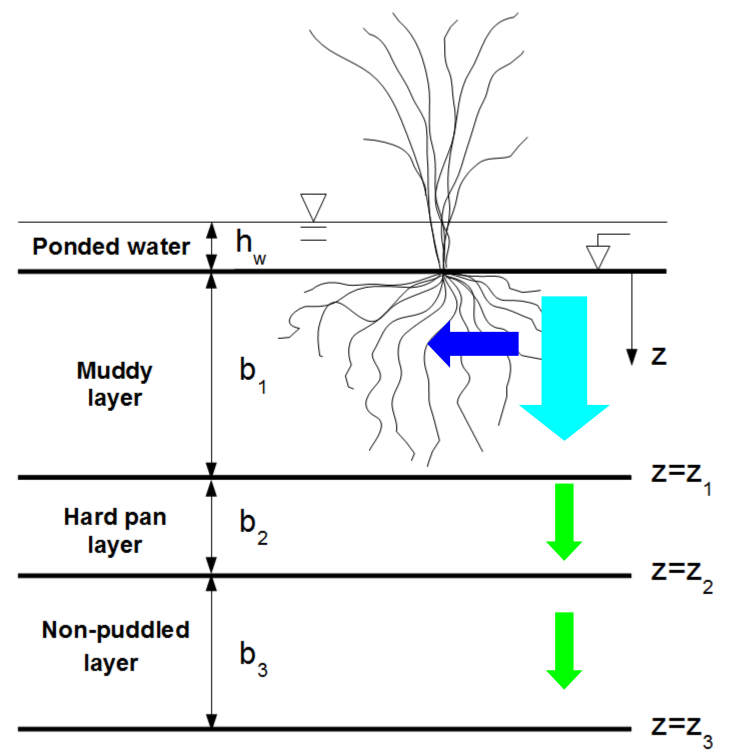
  saturated → Eq. Darcy $\quad \dfrac{\partial}{\partial z}\left(-K_{2,sat}\dfrac{\partial \Phi_2}{\partial z}\right)=0$

- ***Non-puddled layer***

  unsaturated (Eq. Richards)

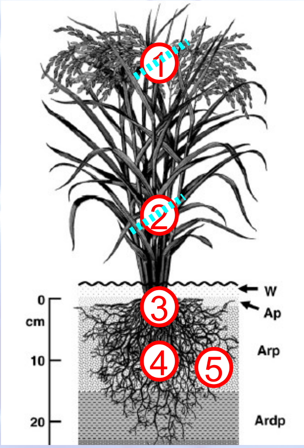
  $H_p(z)$ = cost → $q(z)$=cost

Legend	
K_{sat}	*saturated hydraulic conductivity*
K	*hydraulic conductivity*
Φ	*piezometric head*
H_p	*pressure head*
q	*infiltration rate*



Roots model

- ***Spatial and temporal variability of root features (e.g. biomass)***
  - Exponential root density distribution → spatial variability
  - Plant development function → temporal variability
- ***Plant-root gas conductivity***
  - ① micropores (neglected)
  - ② shoot (neglected)
  - ③ root-shoot
  - ④ root
  - ⑤ root-soil



$$Flux = k(\Delta C)$$

Plant features

- root-shoot → [*Groot et al.*, 2005]
- OPR diffusivity → [*Kotula et al.*, 2009]

- ***Gas mass balance equations within root aerenchyma (PDE system)***
  - O_2 and CH_4
  - Aerenchyma volume
  - Root conductivity
  - O_2 respiration, root-soil flux
  - root-atmosphere exchange → Boundary condition

$$\varepsilon\, RVD \frac{\partial C^g}{\partial t} = -\frac{\partial}{\partial z}\left(\varepsilon\, RVD\, D_a \frac{\partial C^g}{\partial z}\right) + R$$

Biogeochemical model

- ***Mass balance equations (PDE system)***
  - Dissolved species
    - DOC
    - O_2
    - NO_3^-
    - NH_4^+
    - Fe_2^+
    - CH_4
  - Solid species
    - SOC
    - SOC dead root
    - Fe(III)

$$\left(\theta+\rho\frac{\partial C^s_{ads}}{\partial C^l}\right)\frac{\partial C^l}{\partial t}=-\frac{\partial}{\partial z}\left(q\,C^l-\theta\,D_h\frac{\partial C^l}{\partial z}\right)+R+R_p+R_e$$

$$\frac{\partial C^s}{\partial t}=R$$

- Biogeochemical reactions
- **Transport by water flow**
- Dispersive transport
- Root uptake
- adsorption
- ebullition (CH_4)

Legend

C^s_{ads}	*sorbed solid concentration*
C^l	*dissolved concentration*
C^s	*solid concentration*
θ	*soil moisture*
$\rho_,$	*bulk density*
$D_{h,}$	*coefficient of hydrodynamic dispersion*
q	*infiltration rate*
DOC	*dissolved organic carbon*
SOC	*solid organic carbon*

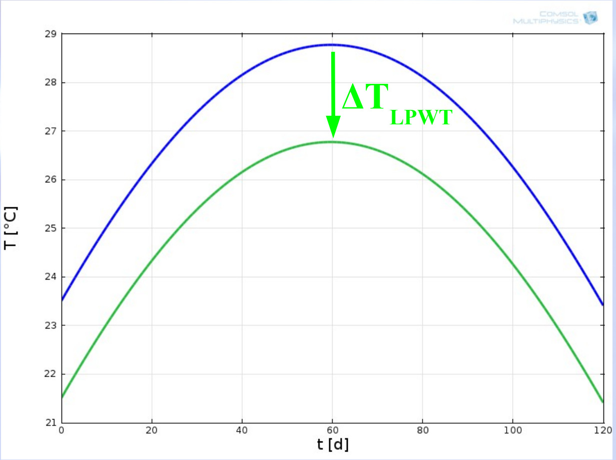
Temperature model

- ***Heat transport equation → soil temperature vertical profile***
  - top BC → sinusoidal ponding water temperature T_w
  - LPWT → $T_w - \Delta T_{LPWT}$
- ***Q_{10} approach***
  - biogeochemical parameters (e.g. kinetic constants)
  - physical parameters (e.g. diffusion coefficients)
  - physiological parameters (e.g. root-tiller conductivity)

$$c\rho\frac{\partial T}{\partial t}=\frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right)-c_W\rho_w q\frac{\partial T}{\partial z}$$

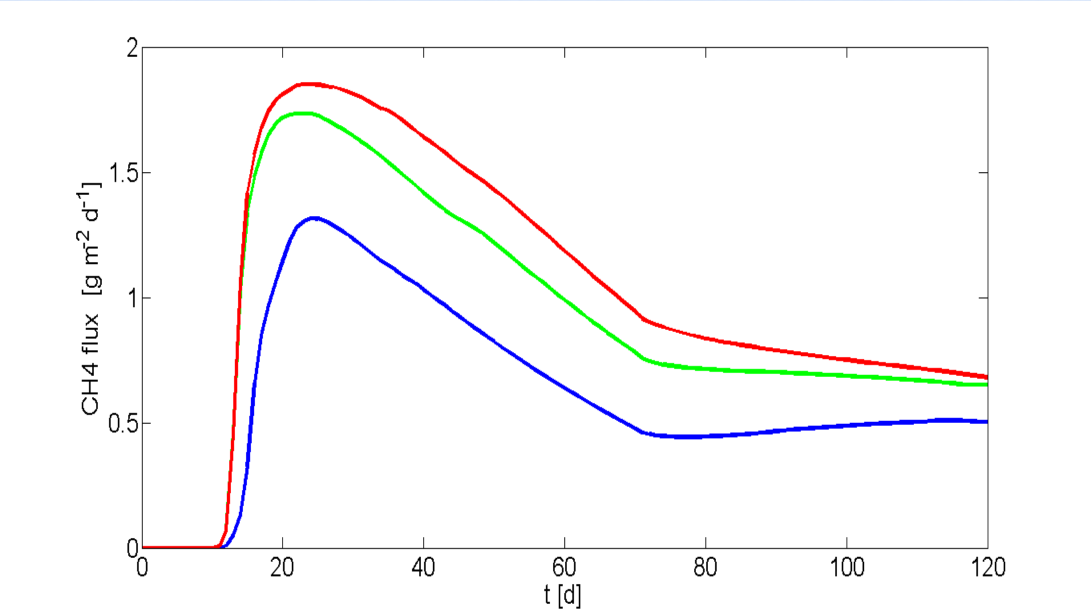
Legend

T soil temperature
c specific heat
ρ density
λ heat conductivity
q infiltration rate



Results: effect of water transport

- ***Simulations***
  - with water fluxes
  - with root water uptake only without percolation (impermeable hard pan) *[Xu et al., 2007]*
  - without water fluxes



Overestimation of CH_4 emissions

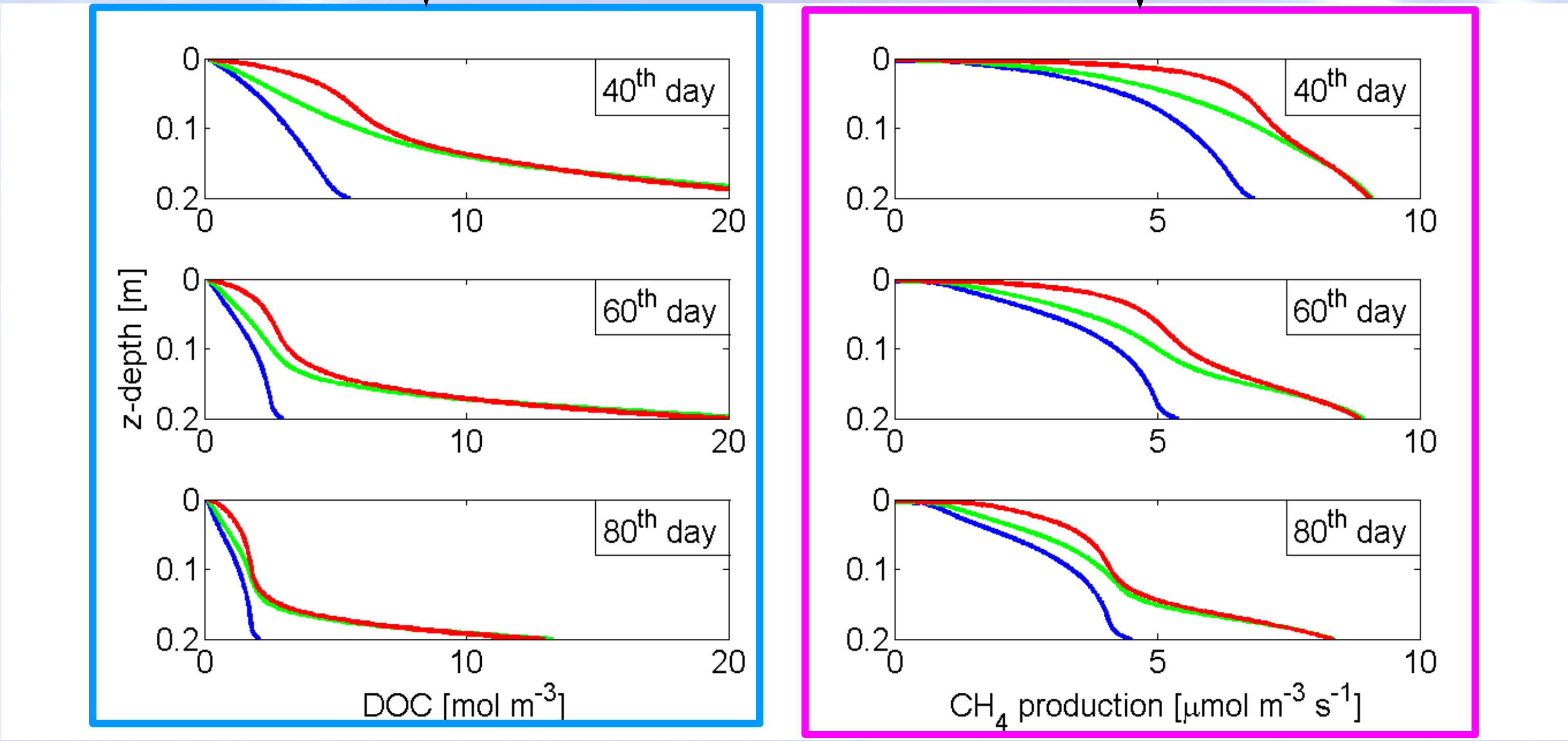
- + 53.7 % on daily minimum
- + 40.8 % on daily maximum
- + 66.8 % on total emissions

Results: effect of water transport

No percolation of dissolved organic carbon

(DOC – energy source for CH_4 production)

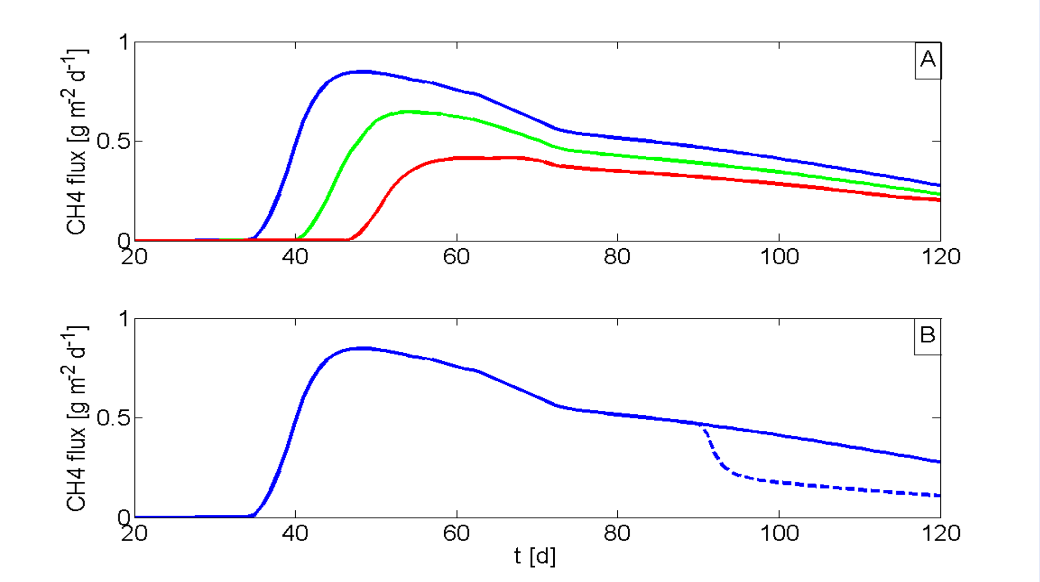
↑↑ DOC concentration → ↑↑ CH_4 production



Results: effect of heat transport → LPWT

- ***Simulations***
  - no LPWT
  - LPWT on the whole growing season (120 days)
    - ΔT_{LPWT} = 1°C → - 26.4 % on total emissions
    - ΔT_{LPWT} = 2°C → - 49.5 % on total emissions
  - LPWT only in the ripening stage (last 30 days - ↓ T sensitive of rice plant ↑ ΔT_{LPWT})
    - ΔT_{LPWT} = 5°C → - 11.9 % on total emissions

Promising reduction of CH_4 emissions



Conclusions

- ***New process-based model for simulate CH_4 emissions from paddy fields***
  - Soil stratigraphy
  - Hydraulic
  - Roots
  - Biogeochemistry
  - Temperature

- ***Results***
  - Effect of water transport: Neglection → simulation of overestimated CH_4 emissions
  - Effect of heat transport: LPWT promising mitigation strategy for CH_4 emissions

- ***Future developments***
  - Modeling N_2O emissions (other GHG)
  - Modeling wet-dry cycle → saturated/unsaturated → CH_4 emissions mitigation
  - Modeling plant eco-physiology → CH_4 mitigation vs. plant stress

Thanks for the attention

For more details see:

Rizzo, A., F. Boano, R. Revelli, and L. Ridolfi 2013, Role of water flow in modeling methane emissions from flooded paddy soils, *Adv. Water Resour.*, 52, 261-274