Greenhouse gas emissions of biofuels, Improving Life Cycle Assessments by taking into account local production factors
Outline

- Context & approach
  - LCA uncertainty related to N₂O
  - variability of N₂O emissions
  - approach for local LCA
- Field experiments & N₂O modelling
  - experimental design
  - observed fluxes
  - modelling results
- Local LCAs of ethanol from sugar beet & Miscanthus
  - goal & scope
  - agricultural data inventory
  - impact assessments
- Conclusions & perspectives
State of the art of biofuel LCAs

Uncertainty in greenhouse gas balance in biofuel LCA
=> due to N\(_2\)O

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Uncertainty (g CO(_2)eq/MJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fossil fuels</td>
<td>≈ 4</td>
</tr>
<tr>
<td>Biofuels</td>
<td>10-40</td>
</tr>
</tbody>
</table>

+ scarce data on 2\(^{nd}\) generation biofuels esp. perennial crops

JRC/EUCAR/CONCAWE 2008
N₂O emissions are highly variable

**Nitrification**: aerobic, co-product

**Denitrification**: anaerobic, intermediary

=> contrasted processes + heterogeneity of factors + varying scales

= high spatial & temporal variability of N₂O emissions

Agricultural management

Volatilization

NH₃

\[ \text{N₂O} \]

\[ \text{NO}_x \]

\[ \text{NO}_2 \rightarrow \text{NO} \rightarrow \text{N}_2 \]

\[ \text{NH}_4^+ \rightarrow \text{NH}_2\text{OH} \rightarrow \text{NO}_2^- \rightarrow \text{NO} \rightarrow \text{N}_2 \]

Wrage et al. 2001

TRENDS in Microbiology

NH₃

NO₃⁻

Leaching

Mineralization

Insects, Nematodes, and other soil animals

Free-living fungi

SOM
Approach for a local LCA

**Goal**: to increase reliability of greenhouse gas balances of biofuels (1st & 2nd generations)

**N₂O**: Main source of uncertainty in biofuel GHG balance

**Main factors** => N₂O emissions

- Agricultural management
- N inputs
- Water content
- Temperature
- SOC
- Soil porosity

**Emission factors**

**Modelled N₂O emissions in biofuel LCAs**

**Agro-ecosystem model**

**Proposed local biofuel LCAs**

**Improving N₂O emission sub-model**

**Context & approach 1.**
- Field experiments & N₂O modelling
- Local LCAs of biofuels
- Conclusions & perspectives

**1.a LCA uncertainty & N₂O**
**1.b Variability of N₂O emissions**
**1.c Local LCA approach**
Outline

- **Context & approach**
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- **Conclusions & perspectives**
Selection of crops and variables

Crops
- energy crops 1\textsuperscript{st} & 2\textsuperscript{nd} generations (annual/perennial)
  - sugar beet: high potential, common crop
  - Miscanthus: high potential, new crop

Treatments
- N fertilization: Miscanthus
- Soil compaction (soil tillage): sugar beet

Flux monitoring
- continuous & frequent measurements
  => high temporal variability

Monitoring of control variables
- soil temperature (-10cm, -20cm)
- soil water content (-10cm, -20cm)
- soil mineral N (NO\textsubscript{3}\textsuperscript{-}, NH\textsubscript{4}\textsuperscript{+}) 0-20 cm
- soil bulk densities 0-30 cm
- climatic data (Agroclim)

Site
- deep loamy soil/agricultural region
- fostered development of bioenergy

Context & approach
1. Field experiments & N\textsubscript{2}O modelling
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3. Conclusions & perspectives
2.a Experimental design
2.b Observed fluxes
2.c Modelled fluxes
Continuous monitoring of CO$_2$ & N$_2$O fluxes

Sugar beet: 2007-2008

- Compacted
- Uncompacted
- CO$_2$ & N$_2$O analysers


- N=0 kg ha$^{-1}$yr$^{-1}$
- N=120 kg ha$^{-1}$yr$^{-1}$

Context & approach 1.
Field experiments & N$_2$O modelling 2.
Local LCAs of biofuels 3.
Conclusions & perspectives 4.

2.a Experimental design
2.b Observed fluxes
2.c Modelled fluxes
Observations: N$_2$O fluxes - sugar beet

Compacted plots
- more emissions = higher + more frequent peaks
- high emissions after fertilization & rainfalls

Uncompacted plots
- emissions more punctual
- peaks also in summer
Observations: N$_2$O fluxes - Miscanthus

<table>
<thead>
<tr>
<th>Year</th>
<th>Fertilized plots</th>
<th>Unfertilized plots</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>peaks after fertilization</td>
<td>very few emissions</td>
</tr>
<tr>
<td>2009</td>
<td>higher emissions than sugar beet</td>
<td>negative fluxes</td>
</tr>
</tbody>
</table>

**Field experiments & N$_2$O modelling**

<table>
<thead>
<tr>
<th>Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. ( \text{Context &amp; approach} )</td>
</tr>
<tr>
<td>2. ( \text{Experimental design} )</td>
</tr>
<tr>
<td>2.b ( \text{Observed fluxes} )</td>
</tr>
<tr>
<td>2.c ( \text{Modelled fluxes} )</td>
</tr>
</tbody>
</table>

_Cécile Bessou_

[Image of graphs showing N$_2$O fluxes for fertilized and unfertilized plots in 2008 and 2009.]
Conclusions on $\text{N}_2\text{O}$ fluxes

Key observations

- higher $\text{N}_2\text{O}$ emissions (+50%) in sugar beet compacted plots compared to uncompacted ones.

- high $\text{N}_2\text{O}$ emissions in *Miscanthus* field when fertilized.

- large **diurnal & seasonal variability**: diurnal amplitude: 125-175% 
  seasonal variability: 75-115% 
  => frequent & continuous monitoring crucial.


- influence of **climate & compaction** > N fertilization doses.

<table>
<thead>
<tr>
<th>kg N-$\text{N}_2\text{O}$ ha$^{-1}$</th>
<th>2007: 100 kg-N</th>
<th>2008: 150 kg-N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compacted</td>
<td>1.45</td>
<td>1.38</td>
</tr>
<tr>
<td>Uncompacted</td>
<td>0.94</td>
<td>0.98</td>
</tr>
</tbody>
</table>
N$_2$O modelling

NOE model (Hénault et al. 2005)

\[
N_2O = r_{\text{NOE}} \left( D_p \cdot F_{N_2O} \cdot F_W \cdot F_T \right) \quad \text{if } WFPS > 0.80
\]

\[
N_2O = z \left( f_{M_H4} \cdot f_W \cdot f_T \right) \quad \text{if } WFPS < 0.62
\]

\[
N_2O = r_{\text{NOE}} \left[ \left( D_p \cdot F_{N_2O} \cdot F_W \cdot F_T \right) + z \left( f_W \cdot f_{M_H4} \cdot f_T \right) \right] \quad \text{if } 0.62 \leq WFPS \leq 0.80
\]

NOE2 model (Bessou et al. 2010 accepted in EJSS)

- adding processes
- variable ratios depending on soil water and nitrate contents
- fine discretization of the vertical soil profile

Observed/simulated (kg N-N$_2$O ha$^{-1}$)

<table>
<thead>
<tr>
<th></th>
<th>Compacted plots</th>
<th>Uncompacted plots</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOE</td>
<td>1.55-0.65</td>
<td>0.11-0.14</td>
</tr>
<tr>
<td>NOE2</td>
<td>1.55-1.03</td>
<td>0.43-0.42</td>
</tr>
<tr>
<td>obs</td>
<td>1.45-1.38</td>
<td>0.94-0.98</td>
</tr>
</tbody>
</table>

2.a  Experimental design
2.b  Observed fluxes
2.c  Modelled fluxes
Observed and modelled N$_2$O fluxes

2007 compacted

....Observed

_ NOE
_ NOE2

Bessou et al.

**Context & approach**
1. Field experiments & N$_2$O modelling
2. Local LCAs of biofuels
3. Conclusions & perspectives

2.a Experimental design
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2.c Modelled fluxes
Observed and modelled N$_2$O fluxes

Context & approach 1.
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Local LCAs of biofuels 3.
Conclusions & perspectives 4.

2.a Experimental design
2.b Observed fluxes
2.c Modelled fluxes
Key conclusions

- Flux kinetics & effect of greater compaction reproduced but global under-estimation:
  - Some high peaks in optimal conditions not reached
  - Effect of dry-wet cycles not modelled

- Compaction => higher denitrification rate (10 folds)
  + Higher z ratios

- Emissions with NOE2 > NOE
  => Enhanced nitrification & ratios (r, z)
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Approach for a local LCA

Local production factors:
- climate
- soil
- management practices

3.a Goal & scope
3.b Agricultural data inventory
3.c Impact assessments

Context & approach 1.
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Conclusions & perspectives
Inventory & Impact categories

Agricultural flows

- modelled: $\text{N}_2\text{O}$, $\text{NO}_x$, $\text{NH}_3$, $\text{NO}_3^-$
- emission factors: $\text{PO}_4^{3-}$, $\text{CO}_2$, $\text{N}_2\text{O}$ indirect

Indicator $i = \sum (\text{substance}_j \times \text{factor}_{ij})$

Impact categories

- Global warming (GWP20, GWP100)
- Stratospheric ozone depletion
- Human toxicity
- Ecotoxicity: freshwater aquatic, marine aquatic, terrestrial
- Acidification
- Photo-oxidant formation
- Eutrophication
- Depletion of aquatic resources

CLM2 Guinée et al. 2002

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Biomass production scenarios

Sugar beet
- 3 rainfall scenarios: R25, R50, R75

Context & approach 1.
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Conclusions & perspectives 4.

3.a Goal & scope
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Biomass production scenarios

**Sugar beet**
- 3 rainfall scenarios: R25, R50, R75
- 2 crop rotations:
  - current = sugar beet-wheat-maize-wheat
  - optimized = incorporation of N input at sowing (-15 kg N ha\(^{-1}\)) + mustard as cover crop (twice)

**Miscanthus**
- 2 fertilizations: 120 kg N ha\(^{-1}\) yr\(^{-1}\)
  - 50 kg N ha\(^{-1}\) yr\(^{-1}\)
## CERES outputs -> LCA inputs

<table>
<thead>
<tr>
<th></th>
<th>Sugar beet</th>
<th>Sugar beet</th>
<th>Miscanthus</th>
<th>Miscanthus</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&quot;baseline rotation&quot;</td>
<td>&quot;optimized rotation&quot;</td>
<td>mean 15 yrs</td>
<td>mean '5 yrs</td>
</tr>
<tr>
<td><strong>N fertilization</strong></td>
<td>Ag N ha⁻¹</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R25</td>
<td>140</td>
<td>125</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>R50</td>
<td>140</td>
<td>126</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R75</td>
<td>140</td>
<td>125</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Mean yields / yr⁻¹</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FM (best) DM (Misc)</td>
<td>71</td>
<td>60</td>
<td>11.2</td>
<td></td>
</tr>
<tr>
<td><strong>Mean NO₂</strong></td>
<td>Ag N-NO₂ ha⁻¹ yr⁻¹</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R25</td>
<td>1.1</td>
<td>1.0</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>R50</td>
<td>1.3</td>
<td>1.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R75</td>
<td>1.2</td>
<td>1.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Mean NO₃⁻</strong></td>
<td>Ag N-NO₃ ha⁻¹ yr⁻¹</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R25</td>
<td>0.9</td>
<td>0.7</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>R50</td>
<td>0.8</td>
<td>0.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R75</td>
<td>0.8</td>
<td>0.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Mean NH₃</strong></td>
<td>Ag N-NH₃ ha⁻¹ yr⁻¹</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R25</td>
<td>4.4</td>
<td>3.3</td>
<td>-1.1</td>
<td></td>
</tr>
<tr>
<td>R50</td>
<td>4.9</td>
<td>3.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R75</td>
<td>7.3</td>
<td>4.9</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Table showing comparative data for different rotations and impacts.*

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### Context & approach
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5. Impact assessments
6. Conclusions & perspectives

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21/44
Potential environmental impacts

Gasoline, Sugar beet ethanol, Miscanthus ethanol

impact indicators relative to the maximum score


3.a Goal & scope
3.b Agricultural data inventory
3.c Impact assessments
Effect of local factors

Rainfall scenarios (beet)
- variability: 1%-60% savings
- R25 more severe impacts (R50~R75)
  except for eutrophication

Rotation scenarios (beet)
- variability: 1%-15% of savings
- optimized rotations more
  severe impacts
  except for acidification &
eutrophication

Fertilization scenarios (Misc.)
- 1%-15% savings
Trade-off due to varying FU

- **trade-off ha/MJ** between current & optimized crop rotations
- yield effect particularly important for Miscanthus
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- Conclusions & perspectives
Conclusions on LCAs

Key results

- **biofuels vs fossil fuels**
  - lower impacts: **abiotic resources, climate change, ozone**
  - higher impacts: **eutrophication, acidification, toxicities**
  - *Miscanthus* (2nd generation): **much lower impacts**
  - savings in GHG ethanol beet: **28-42%, Miscanthus: 82-85%**

- **effect of local factors**
  - across rainfall scenarios **5-15% (max 60%)** of savings
  - 2 fertilizations on *Miscanthus** **3-5% (max 15%)** of savings
  - **optimized scenarios** (cover crops => lower impacts) but lower yields
  - **trade-off**: low impact (ha⁻¹) => high (MJ⁻¹) if low yield ha⁻¹
LCA in perspectives

- local LCAs => a **tool for decision-making** purpose within the frame of biofuel certification

- how to account for land use change?
  - optimization on ha or MJ basis?
  - what happens after *Miscanthus*?
  => adding a quantitative assessment of **soil carbon change**:
    - C storage after perennials
    - step by step accounting for CO$_2$

- what is the indirect impact on other lands?
  => adding a **qualitative assessment**:
    - including socio-economic factors
    - LCA combined with other assessments/models
    - taking into account change in biodiversity
Thank you!