Bio-energy and residue use:

Nutrient recovery from bio-digestion waste and reuse as chemical fertilizer substitutes

Bio-energy workshop

Lund University

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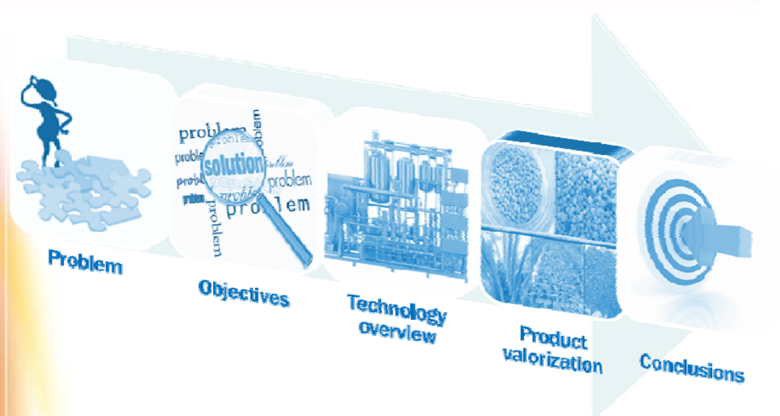
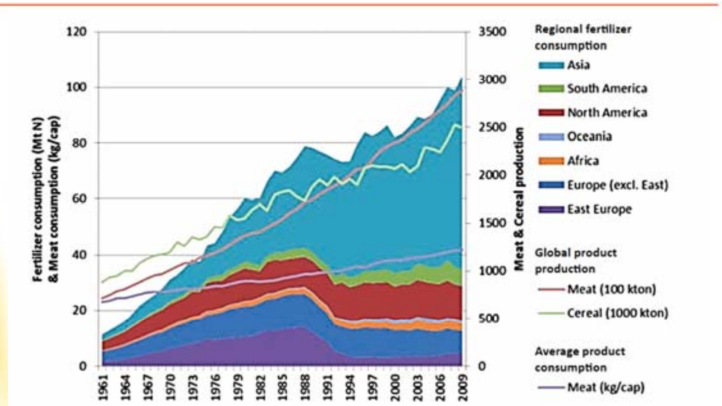
Presentation outline



PROBLEM STATEMENT

Global use of chemical fertilizers



Demand ↑ ⟹ Energy use ↑ ⟹ Costs ↑

Sutton et al. (2013)

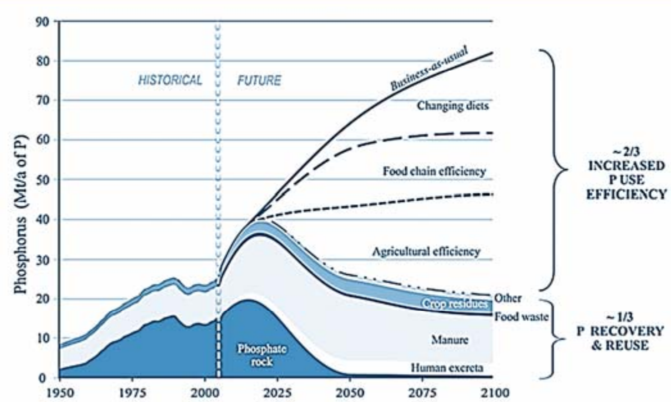
Energy use and costs for chemical fertilizers

Mining

		N	P_2O_5	K_2O	Unit	Reference
ENERGY	Production	70	7.7	6.4	GJ/ton	Gellings & Parmenter (2004)
	Packing	2.6	2.6	1.8	GJ/ton	Gellings & Parmenter (2004)
	Transport	4.5	5.7	4.6	GJ/ton	Gellings & Parmenter (2004)
	Application	1.6	1.5	1.0	GJ/ton	Gellings & Parmenter (2004)
	Total	78	18	14	GJ/ton	Gellings & Parmenter (2004)
COSTS	Total	1.037	0.956	0.625	euro/kg	Aveve (2011)

Energy-intensive
Haber Bosch process

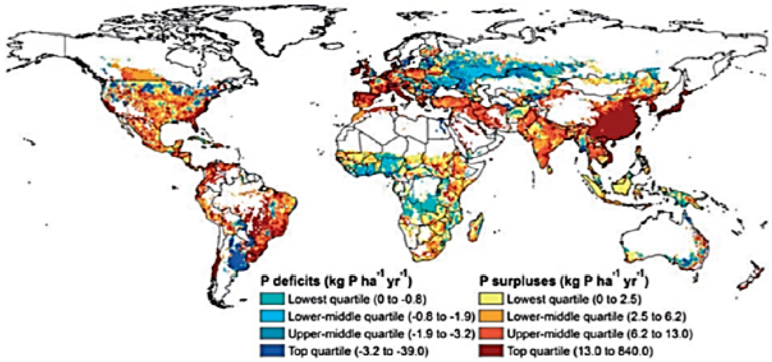
Increasing demand vs. threatening depletion



Natural resources ↓ ⟹ Quality ↓

Cordell et al. (2011)

On the other hand:
nutrient excesses in the environment



Sutton et al. (2013)

Environmental concerns

A PARADOX EXISTS…

Nutrient excesses in the environment from sewage, animal manure, digestate, waste water, ashes, etc.

Increasing demand for chemical fertilizers

Environmental pollution

Stringent fertilization and discharge levels = processing of waste required

Nutrient depletion (P, K)
Price ↑, quality ↓

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Need for sustainable resource management !

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OBJECTIVES

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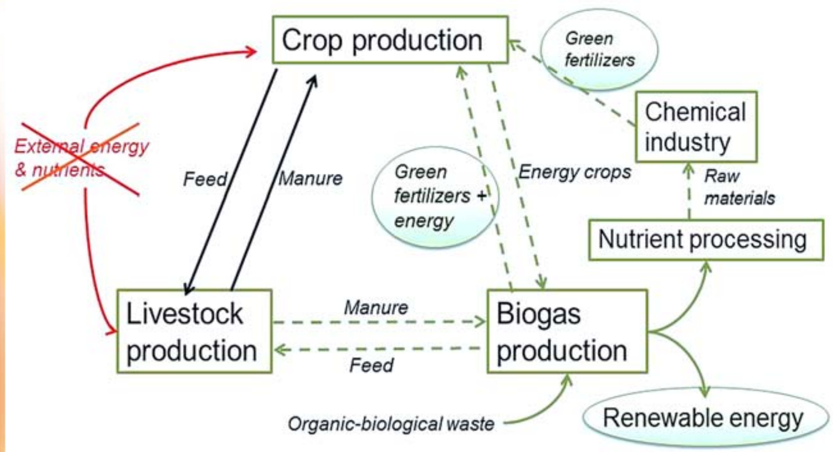
Cradle-to-cradle nutrient recycling



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Specific objectives (1)

1. To create a systematic overview of technologies for nutrient recovery from bio-waste and classify the resulting end-products

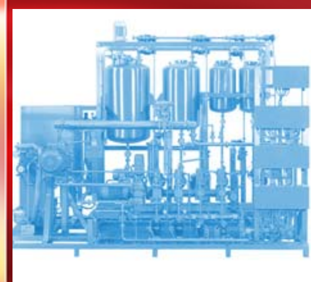
2. To evaluate the fertilizer potential and identify potential bottlenecks for agricultural reuse of recovered products as substitute for chemical fertilizers and/or as P-poor equivalent for animal manure

Specific objectives (2)

3. To evaluate the impact of these renewable fertilizers on soil quality and crop production by means of greenhouse and field experiments

4. To assess an economic and ecological evaluation of the cradle-to-cradle use of these products in agriculture

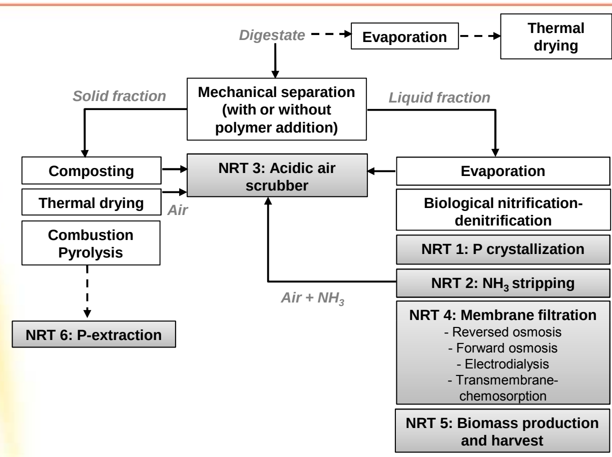
NUTRIENT RECOVERY TECHNOLOGY (NRT) OVERVIEW



Points of attention

- The nutrient recovery process must have equivalent treatment efficiency as conventional treatment
- The process must be cost-effective
- The process must be simple to operate and maintain
- <u>There must be a market for the recovered nutrient products</u>

Extraction of nutrients after anaerobic digestion



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NRT 1: P crystallization

- Soluble P (ortho-phosphate) can be precipitated by:
  - $Ca^{2+} \rightarrow Ca_3(PO_4)_2$
  - $Mg^{2+} \rightarrow MgNH_4PO_4.6H_2O$ or $MgKPO_4.6H_2O$ (MAP of struvite)
  - $K^+ \rightarrow K_2NH_4PO_4$ (potassium-struvite)
- Status: Full-scale for waste water, digested centrate and calf manure; Pilot scale for raw digestate
- Valorisation end-product: Slow release fertilizer
- Economic viability
  - Slow release fertilizer
  - Elimination of Fe/Al

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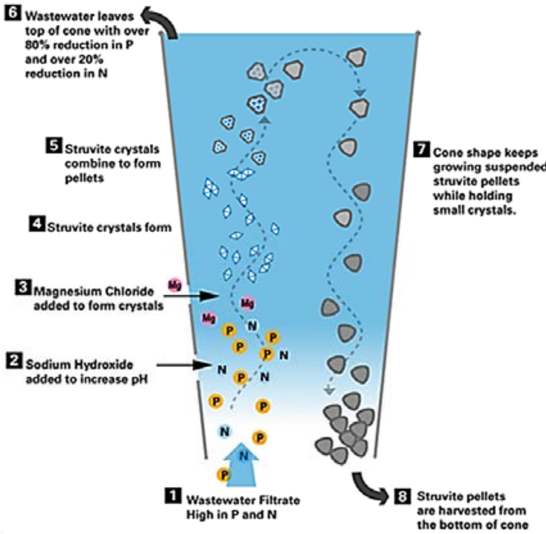
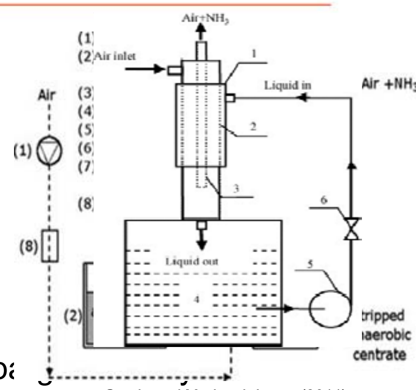


Multiform Harvest (2013)

Design: Fluidized bed reactor
or continuously stirred tank reactor

NRT 2: NH_3-stripping and absorption

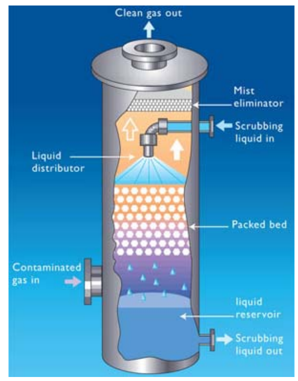
- Mass transfer of NH_3 from aqueous to gas phase
  - Elevated pH & T
  - Lime softening step
- Design: Packed column
  - Status: Full-scale
  - Bottlenecks: Fouling of the packing material
- Improved design: Water-spa
  - Status: Lab-scale (Quan et al. 2010)
  - Higher air stripping efficiency, better mass transfer



Gustin and Marinsek-Logar (2011)

NRT 3: Acidic air scrubber

- Capture of NH_3, dust particles, water vapour, odour compounds in acid, mostly H_2SO_4
  - $NH_3 + H_2SO_4 \rightarrow (NH_4)_2SO_4$
- Design: Packed bed reactor or venturi scrubber
  - Bottleneck: Corrosion problems
- Status: Full-scale
- Valorisation end-product
  - Sulphur content (30-40 kg m^{-3}) !
  - Variable N-content (30-70 kg m^{-3})
  - Low pH (3-7), high salt content



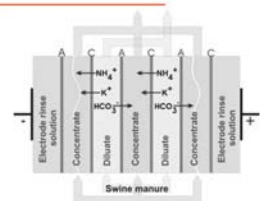
http://www.croll.com/wetscrubbers.html

NRT 4: Membrane filtration

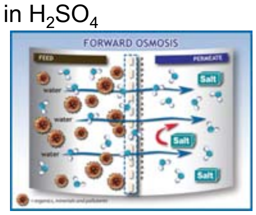
- Types: RO, UF, MF
- Valorisation end-product: N/K fertilizer (RO)
  - Variable N (2-10 g kg^{-1}) and K_2O (4-14 g kg^{-1}) content
  - High salt content
- Status: Full-scale for digestate and manure
- Bottleneck: Blocking of membranes (SS, salts, …)
- Economic viability
  - High chemical requirements
  - High energy use
  - High operational costs

Emerging membrane techniques

- Electrodialysis
  - Ion exchange membrane + electrical voltage
  - Transfer of NH_4^+, K^+ en HCO_3^-
  - Status: No full-scale for digestate, tests on lab-scale



- Transmembrane chemosorption
  - Diffusion of NH_3 through membrane & capture in H_2SO_4
  - Status: Pilot in NL (pig slurry)
- Forward osmosis
  - Use of draw solution instead of pressure (RO)
  - Status: Full-scale for sea water, food waste; no testing (?) with digestate



NRT 5: Biomass production and harvest

- Removal of P&N by plant uptake (algae, duckweed)
- Status: Lab tests (algae) + pilots
- Bottlenecks
  - Suspended solids, humic acids,... → reduction of light penetration
  - Large surface required
  - High energy consumption and high costs
  - Harvest method
- Valorisation harvested biomass
  - Bio-based chemicals or fertilizer
  - Biofuels
  - Animal feed

Comparison of technologies and end-products

Technique	P-crystallisation	NH_3- stripping & air scrubbing	Membrane filtration	Biomass production
% recovery	80-90 % P 0-40 % N	> 90 % N	Depends on pretreatment	80-90 % N and P
End-products	Struvite or Ca-P crystals = Slow-release fertilizer	$(NH_4)_2SO_4$ solution = N-S fertilizer	N-K-fertilizer (RO)	Biomass: Duckweed (30 % P on DW)
Main technical bottlenecks	➢ Precipitation in piping/equipment	➢ Fouling / corrosion	➢ Membrane blocking	➢ Harvest method ➢ Reduced light penetration
Ecological evaluation	➢ Chemical use ➢ Fe/Al ↓	➢ Odor ↓ ➢ Energy ↑ ➢ Acid ↑ ➢ Can replace N-D	➢ Chemicals ↑ ➢ Energy ↑	➢ Surface ↑ ➢ Energy ↑ ➢ Use of polymers
Economic evaluation	Can be profitable	➢ Can replace N-D ➢ Interest in S ↑	High capital and operational costs	High costs (algae)

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Conclusions: Technology overview

- Best available technologies for nutrient recovery:
  - Struvite precipitation
  - NH_3-stripping and absorption in acidic air scrubber
- Further technical fine tuning
  - Fertilizer quality
  - Energy and chemical reduction
- Further developments will only take place if recovery is profitable

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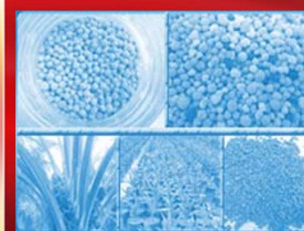
Product valorization



Field experiment Wingene, Flanders

Eight fertilization scenarios

- Dosage of effective N and K_2O based on fertilizer analysis and soil advice (135/150 kg effective N/ha, 80 kg P_2O_5/ha, 180/250 kg K_2O/ha)

Year	Synthetic Start N[a]	Synthetic N[a]	Air scrubber water	Animal manure	Digestate micture[a]	Liquid fraction digestate	Synthetic K_2O[a]	Total P_2O_5
	kg N/ha	kg N/ha	kg N/ha	kg N/ha	kg N/ha	kg N/ha	kg K_2O/ha	kg P_2O_5/ha

Reference

Substitution of chemical fertilizer by air scrubber waste water

Anaerobic co-digestion of animal manure and use of digestate as fertilizer, with and without the substitution of chemical fertilizer by air scrubber waste water

Use of the liquid fraction of digestate as P-poor fertilizer, with and without the substitution of chemical fertilizer by air scrubber waste water

Four replications (n = 4)

Strip of land			
obj 7	obj 8	obj 2	obj 5
obj 1	obj 4	obj 3	obj 4
obj 2	obj 5	obj 1	obj 6
Strip of land			
obj 3	obj 6	obj 7	obj 8
obj 2	obj 4	obj 7	obj 8
Strip of land			
obj 1	obj 5	obj 3	obj 6
obj 3	obj 6	obj 2	obj 5
obj 7	obj 8	obj 1	obj 4
Strip of land			

Fertilizer application

Pc-controlled injection (Boco-trance)

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Sampling of plant and soil

2011 and 2012: Apr (soil), Jul, Sept, Oct (harvest), Nov

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Physicochemical analysis

PLANT	SOIL
▪ Yield ▪ Fresh & dry weight, N, P, K, Ca, Mg, Na, S, metals ▪ Biogas potential (biogas batch test 37 ºC)	▪ 0-30 cm: dry weight, pH-H_2O, pH-KCl, EC, N, NO_3, NH_4, P, K, Ca, Mg, Na, S, metals, Cl^-, extractable nutrients ▪ 30-60 cm, 60-90 cm: dry weight, NO_3

Statistical analysis

STATISTICS	MODELLING
▪ Effect of fertilizer type on plant yield and DW-content, plant nutrient uptake, nutrient soil contents and soil quality parameters: One-way Anova ($\alpha = 0.05$; $n = 4$) ▪ Post hoc pair-wise comparisons: Tukey's HSD Test ($\alpha = 0.05$; $n = 4$) ▪ Normality: Kolmogorov Smirnov test and QQ-plots ▪ Homoscedasticity: Levene Test ▪ Significant parameter correlations: Pearson correlation coefficient (r)	▪ Nutrient balances: Computer model NDICEA *(Nitrogen Dynamics In Crop rotations in Ecological Agriculture)* nitrogen planner 6.0.16 ▪ Input: Physicochemical product, plant and soil analyses (3 year real data), particular weather conditions for the test site ▪ Simulations over 3 and 30 years ▪ Comparison with calculated nutrient balances (nutrient inputs – crop nutrient uptake)

Visual results

- June 4 2011: Simultaneous growth

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Visual results

- June 19 2011: Simultaneous growth

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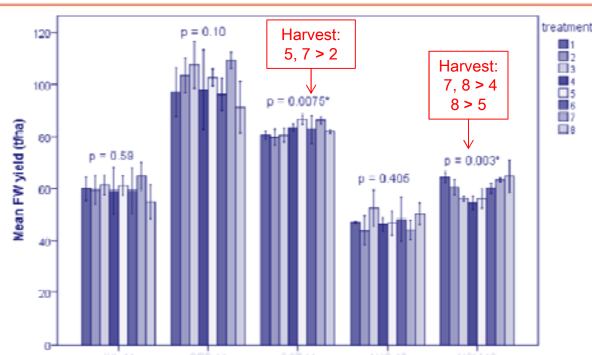
Visual results

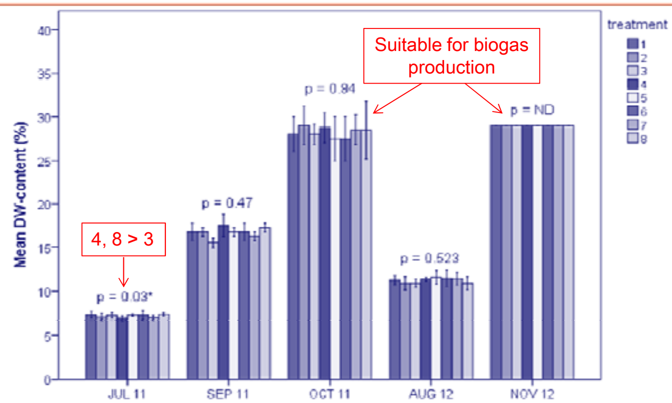
- Aug 20 2011:
  Plant ±3.60 m
  Cob formation

Fresh weight biomass yield



- No significant differences with the reference
- Sc 7 (use of LF digestate) always relatively high biomass yield

Dry weight content



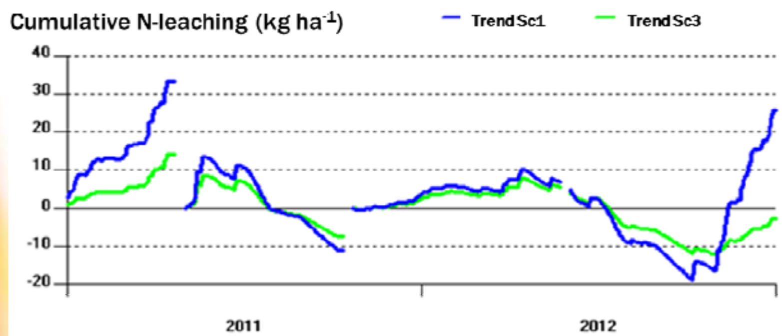
No significant differences with the reference scenario

Biogas potential

Scenario	DW (%)	Residence time (d)	Biogas ($Nm^3\ ton^{-1}$ FW)	CH_4 ($m^3\ ha^{-1}$)	Energy ($GJ\ ha^{-1}$)	Electricity ($MWh_{el}\ ha^{-1}$)	Heat ($MWh_{th}\ ha^{-1}$)
1	28	42	136	6309 ± 156	200 ± 5	22 ± 1	24 ± 1
2	29	34	143	6536 ± 245	207 ± 8	23 ± 1	25 ± 1
3	28	36	135	6260 ± 232	198 ± 7	22 ± 1	24 ± 1
4	29	39	140	6659 ± 80	211 ± 3	23 ± 0	26 ± 0
5	27	37	131	6536 ± 150	207 ± 5	23 ± 1	25 ± 1
6	28	42	135	6383 ± 384	202 ± 12	22 ± 1	25 ± 1
7	28	41	139	6818 ± 79	216 ± 3	24 ± 0	26 ± 0
8	29	37	140	6558 ± 80	208 ± 3	23 ± 0	25 ± 0

No significant differences in biogas potential of harvested crops (n=4, α=0.05)

Modelling N dynamics



- Sc 3 vs. 1: less N losses in the environment when replacing chemical N fertilizer by acidic air scrubber water

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Calculated nutrient balances

kg ha^{-1}	Scenario 1				Scenario 2				Scenario 3			
	N-3[a]	N-30[a]	P_2O_5	K_2O	N-3[a]	N-30[a]	P_2O_5	K_2O	N-3[a]	N-30[a]	P_2O_5	K_2O
Manure application	186	186	76	216	186	186	76	216	186	186	76	216
Deposition	30	30	3	8	30	30	3	8	30	30	3	8
Total application	216	216	79	224	216	216	79	224	216	216	79	224
Removal with products	228	228	77	301	240	240	76	292	251	251	82	271
Calculated surplus	-12	-12	1	-77	-24	-24	2	-69	-36	-36	-4	-48
Volatilization	15	15			16	16			17	17		
Denitrification	6	3			5	3			6	3		
Leaching	45	24			41	18			31	2		
Organic matter	-50	-20			-66	-21			-82	-20		

[a]N-3 and N-30: simulation over 3 and 30 years

Sc 1→3: substitution chemical N by air scrubber water ↑
=> N-leaching ↓, P_2O_5 extraction ↑, chemical K_2O requirements ↓

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Soil quality

- No significant effect on soil EC, pH-H_2O, pH-KCl, sodium adsorption ratio, S-content and heavy metal accumulation
- Significantly more organic carbon in scenario 4-8

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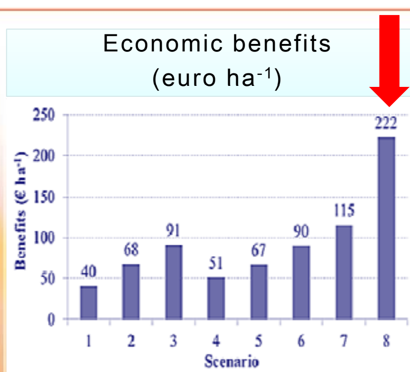
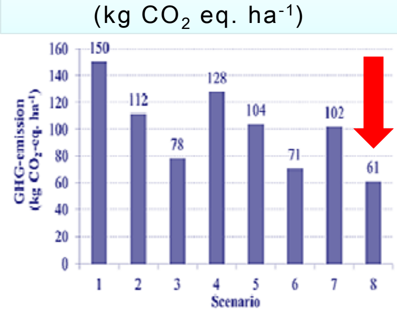
Economic and ecological evaluation

Economic benefits (euro ha^{-1})	Greenhouse gas emission (kg CO_2 eq. ha^{-1})





Sc 8: Use of liquid fraction of digestate and complete elimination of chemical fertilizers

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Conclusions: product valorization

- Recycling of nutrients from bio-digestion waste derivatives in agriculture can:
  - create sustainable substitutes for chemical fertilizers with high nutrient use efficiencies
  - reduce NO_3-leaching and increase soil P_2O_5 recovery
  - result in economic and ecological benefits

Recommendations and perspectives

Recommendations

- The use of recovered bio-based products should be encouraged in environmental and fertilizer legislations
- Need for greater differentiation between fertilizer types, soils and crops in the recommendations given on nutrient requirements
- Stimulation of green fertilizer use in environmental legislation = stimulation of bio-energy production and resource recovery (2020 directives !)

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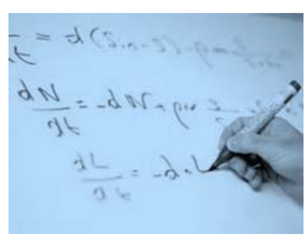
Research perspectives

- Validation of results in the longer term, for different soil types and for other products
- model*EAU* / Primodal:
  Dynamic modelling of ad and physico-chemical nutrient recovery systems to sustainably produce marketable fertilizers with high nutrient use efficiency (BMP Innovation, NSERC/FRQNT)



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