Institute for Agricultural and Fisheries Research

Biochar and soil nitrogen dynamics

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Overview

1. Nitrogen cycle
2. Nitrogen availability
3. Nitrogen transformations in soil
4. Greenhouse gas emissions
5. Conclusions

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Overview

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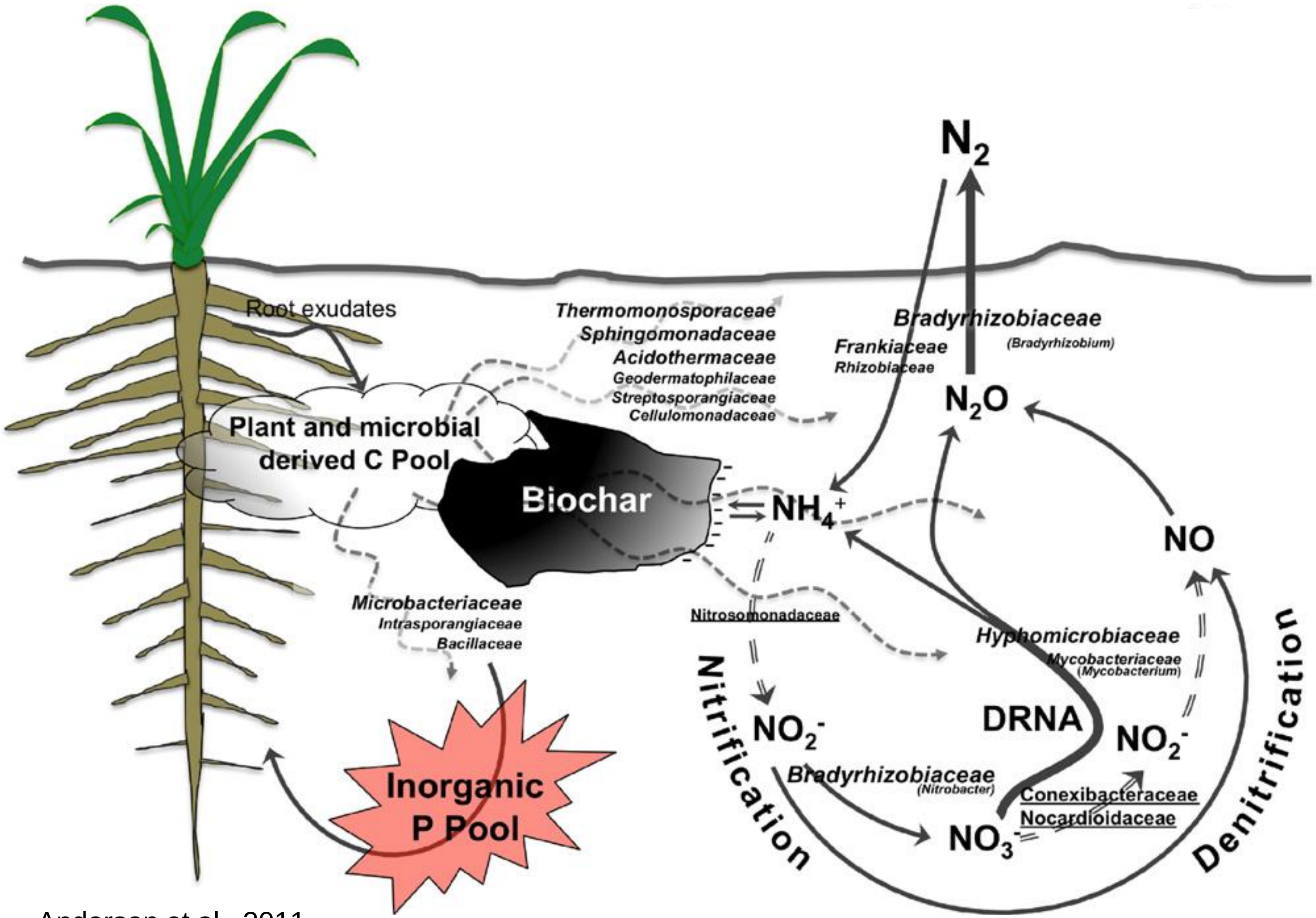
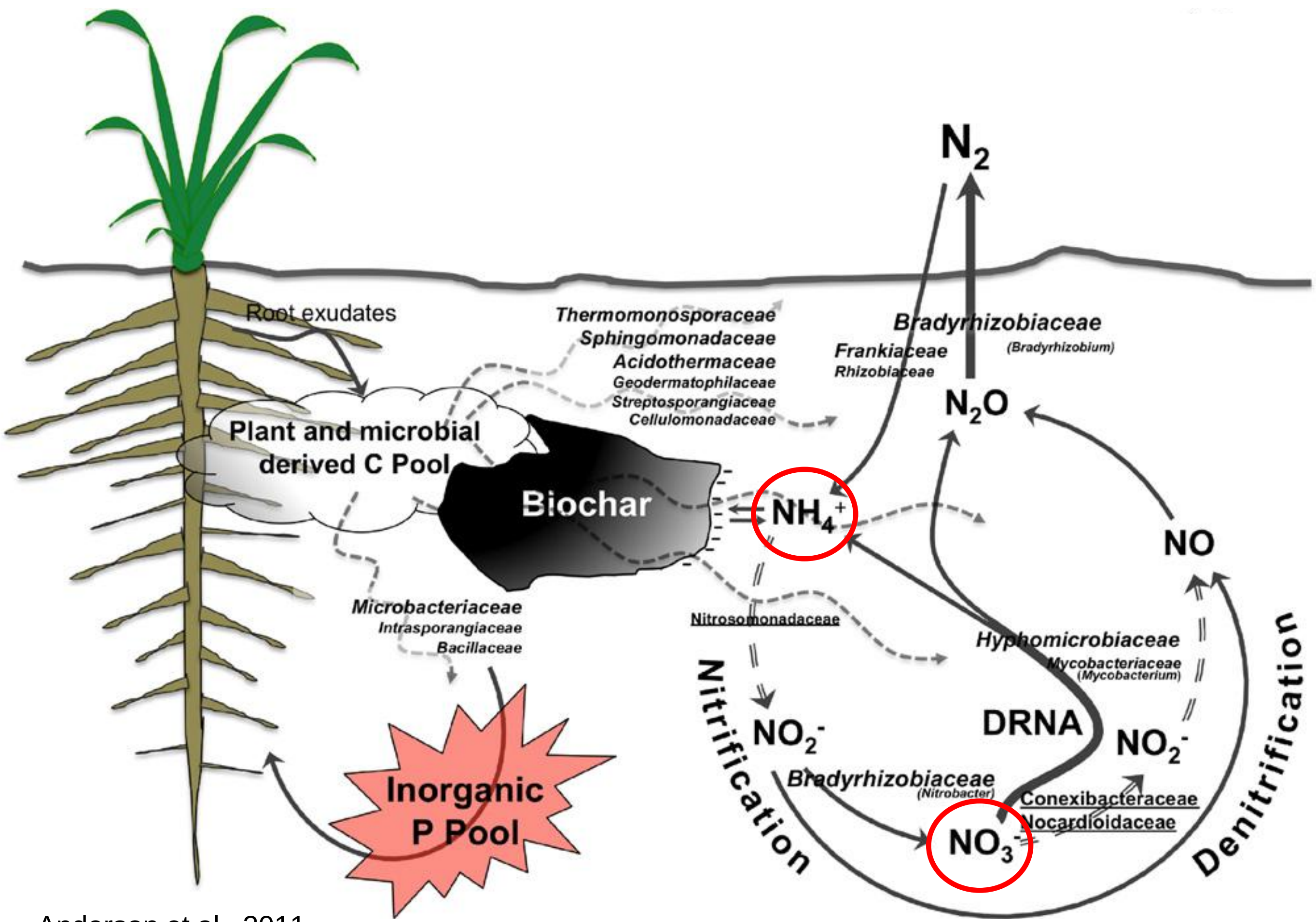
1. Nitrogen cycle



Anderson et al., 2011

1. Nitrogen cycle



Anderson et al., 2011

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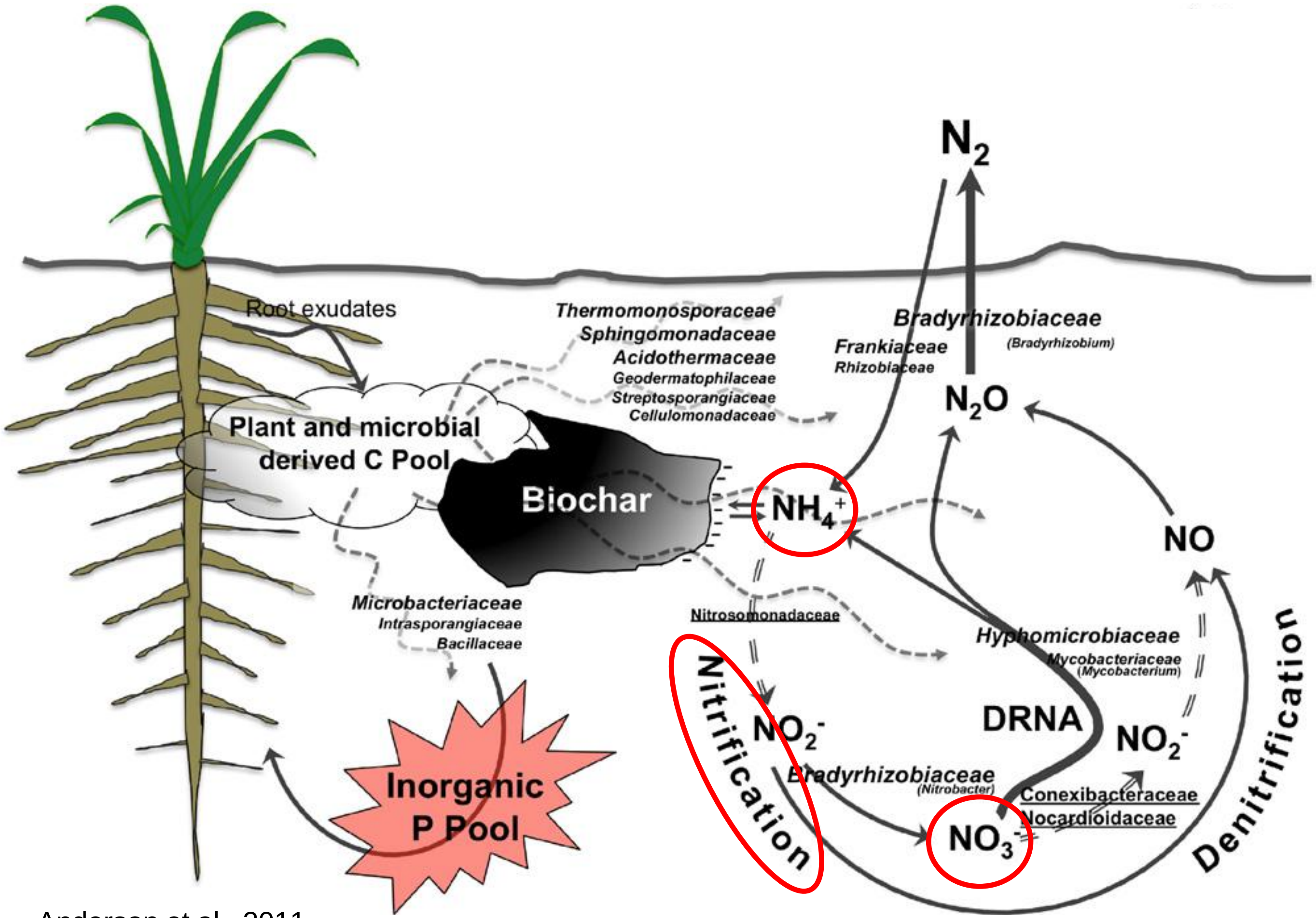

Anderson et al., 2011

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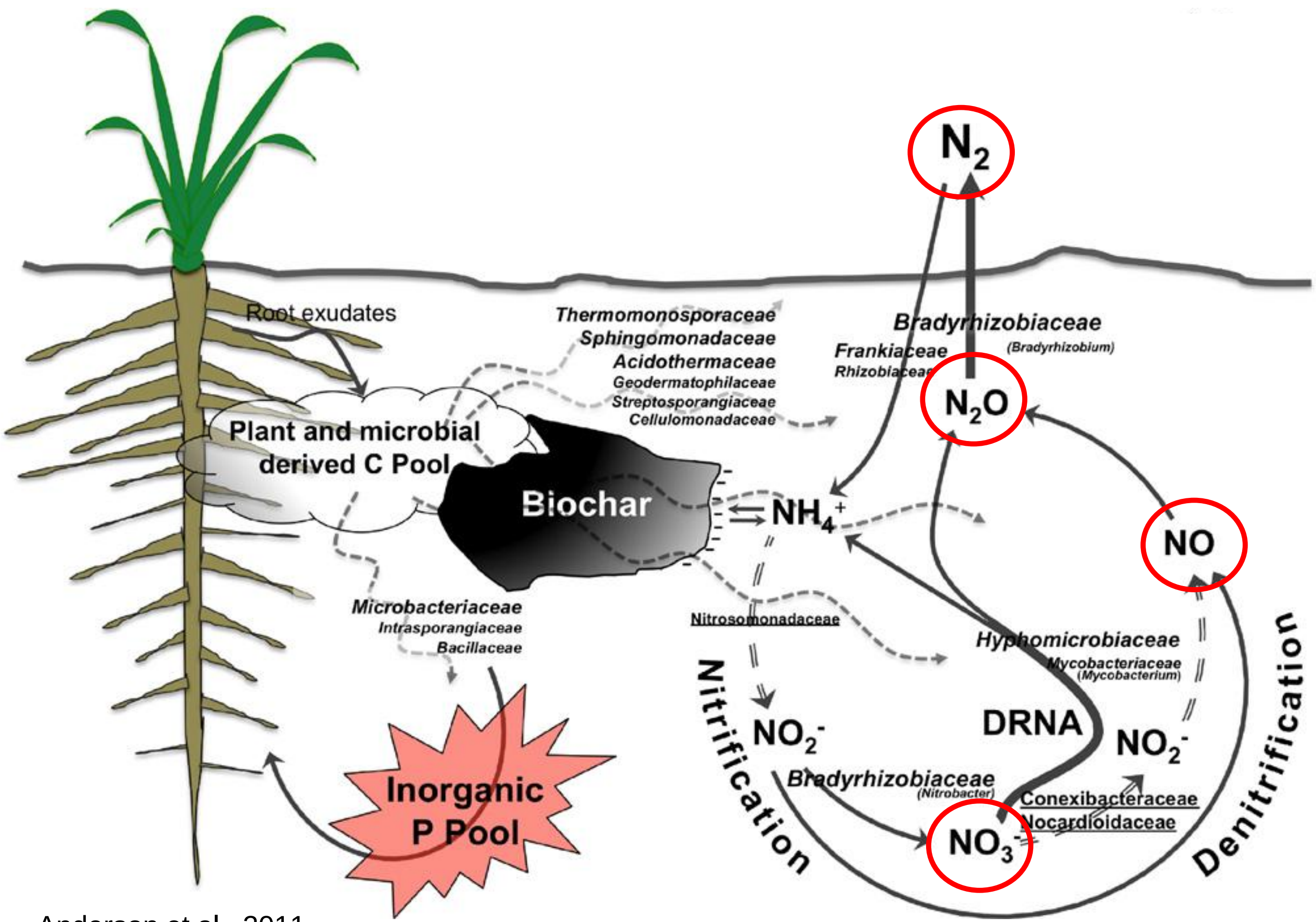

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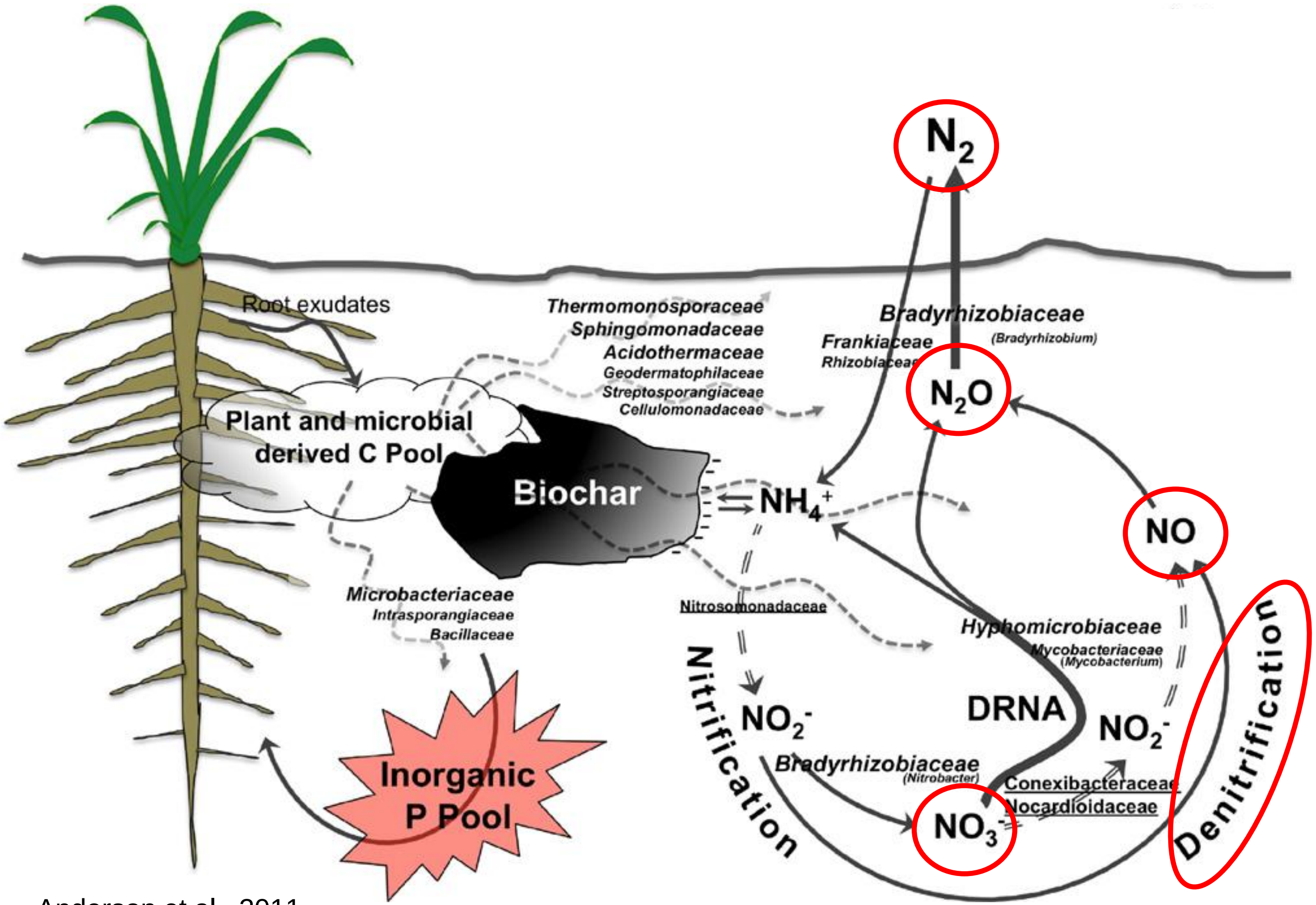

Anderson et al., 2011

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2. Nitrogen availability

Effect of biochar on mineral N availability:

- Biochar composition: depending on temperature + feedstock

Manure ⟷ Wood

Manure	Wood
Macronutrients (N, P)	Higher C:N ratio
Ash	Biotic N immobilization

- Physical entrapment of mineral N in biochar pore structures
- NH_3 losses/adsorption
- Capacity of biochar to retain and exchange nutrients (CEC, AEC)

2. Nitrogen availability

CEC

CEC ↗ when T ↗ ⟷ CEC ↘ when T ↗

Feedstock	Temp (°C)	CEC ($cmol_c$/kg)
Willow	450	33,4
Willow	550	42,8
Willow	650	59,1
Pine	450	38,6
Pine	550	52,1
Pine	650	68,8
Maize	350	55,2
Maize	550	61,9

(Nelissen et al., 2013)

Table 2a. Means and standard errors for pH, CEC, and total macronutrient concentrations in poultry litter, peanut hull, and pine chip biochars. Feedstock and temperature columns indicate significant differences ($p < 0.05$, $n = 3$).[a]

	Poultry Litter (PL)				Peanut Hulls (PN)				Pine Chips (PC)					
	400 °C		500 °C		400 °C		500 °C		400 °C		500 °C			
	Biochar	SA	Biochar	SA	Biochar	SA	Biochar	SA	Biochar	SA	Biochar	SA	Feedstock	Temp
pH (S.U.)	10.1 ±0.04	10.1 ±0.07	9.74 ±0.05	9.88 ±0.09	10.5 ±0.05	10.5 ±0.10	10.1 ±0.02	9.96 ±0.01	7.55 ±0.09	7.99 ±0.09	8.30 ±0.15	8.10 ±0.60	PC<PL<PN	
CEC (cmol kg^{-1})	61.1 ±0.73	57.4 ±1.4	38.3 ±1.7	37.0 ±1.6	14.2 ±0.46	11.7 ±2.04	4.63 ±0.10	4.46 ±0.13	7.27 ±0.54	6.00 ±0.11	5.03 ±0.85	6.02 ±3.12	PC<PN<PL	500<400
C (g kg^{-1})	392 ±3.8	399 ±7.4	392 ±8.6	421 ±23	732 ±14	762 ±3.4	804 ±1.7	806 ±5.8	739 ±17	761 ±3.6	817 ±1.9	820 ±17	PL<PN, PC	400<500
N (g kg^{-1})	34.7 ±0.79	34.7 ±0.77	30.9 ±0.89	32.3 ±1.6	24.3 ±0.18	24.0 ±0.37	24.8 ±0.89	24.8 ±0.34	2.55 ±0.40	1.95 ±0.06	2.23 ±0.09	2.20 ±0.12	PC<PN<PL	500<400
P (g kg^{-1})	30.1 ±0.16	32.2 ±2.3	35.9 ±1.6	34.8 ±2.6	1.83 ±0.11	1.70 ±0.12	1.97 ±0.03	2.06 ±0.11	0.15 ±0.004	0.14 ±0.004	0.14 ±0.02	0.20 ±0.02	PC<PN<PL	400<500
K (g kg^{-1})	51.1 ±1.3	52.6 ±4.9	58.6 ±2.9	54.7 ±1.5	15.2 ±0.58	14.40 ±1.40	16.4 ±0.19	16.5 ±0.79	1.45 ±0.06	1.51 ±0.07	1.45 ±0.18	2.25 ±0.25	PC<PN<PL	400<500
Ca (g kg^{-1})	42.7 ±0.30	45.7 ±3.0	50.4 ±2.2	49.1 ±3.7	4.62 ±0.06	4.46 ±0.29	5.12 ±0.12	5.21 ±0.20	1.71 ±0.11	1.69 ±0.02	1.85 ±0.14	2.17 ±0.04	PC<PN<PL	400<500
Mg (g kg^{-1})	10.7 ±0.23	11.4 ±0.91	12.9 ±0.50	12.4 ±1.0	2.19 ±0.06	2.17 ±0.16	2.50 ±0.05	2.59 ±0.11	0.60 ±0.04	0.58 ±0.03	0.59 ±0.06	0.76 ±0.01	PC<PN<PL	400<500
S (g kg^{-1})	13.67 ±0.39	12.3 ±0.09	13.93 ±1.1	13.9 ±0.37	0.56 ±0.02	0.51 ±0.03	0.55 ±0.09	0.37 ±0.09	0.01 ±0.04	0.16 ±0.05	0.06 ±0.01	0.08 ±0.04	PC, PN<PL	

[a] SA = steam activation.

(Gaskin et al., 2008)

Loss of acidic surface functional groups when temperature ↗

2. Nitrogen availability

CEC

Country	Year	Biochar	Dose t/ha	Crop	Soil type	Type of experiment	Ref.
AUS	2010	Wood mixture	0, 5, 10, 20, 50	Radish	Sandy, low pH	Pot	Van Zwieten et al., 2010

Short term

Table 3. Main effects of biochar on selected soil properties at the completion of the glasshouse trial averaged over N application

Biochar rate (%):	0	1.1	2.2	4.4	11	s.e.	l.s.d.
$pH(CaCl_2)$	4.85	4.82	4.84	4.95	4.89	0.04	0.11
Total C (%)	2.25	2.50	2.93	3.83	6.61	0.28	0.79
Walkley–Black C (%)	1.92	2.05	1.99	1.95	2.12	0.05	0.13
Total N (%)	0.26	0.25	0.25	0.27	0.25	0.01	0.04
NH_4^+-N (mg/kg)	8.51	6.19	7.51	6.42	4.70	1.00	2.84
NO_3^--N (mg/kg)	5.85	8.03	5.67	4.67	13.87	1.92	5.43
Bray P (mg/kg)	452	448	443	432	436	5.2	
Total P (%)	0.10	0.11	0.11	0.09	0.09	0.001	
EC (dS/m)	0.07	0.07	0.07	0.06	0.08	0.004	
CEC ($cmol_{(+)}$/kg)	4.90	5.04	4.96	4.86	4.79	0.07	
Biomass C (mg C/kg)	0.25	0.20	0.24	0.18	0.31	0.03	
FDA (μg fluorescein/g soil)	1.31	1.27	1.40	1.33	1.55	0.04	

CEC =

Long term

Due to oxidation of biochar in soil ➔ CEC ↗

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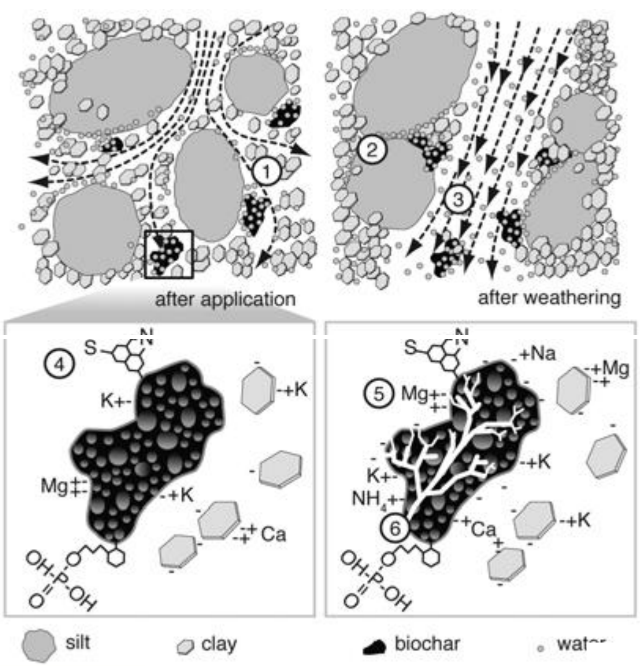
2. Nitrogen availability

Nutrient use efficiency

- CEC
- Water retention
- Microbial N immobilisation



Schematic representation of proposed biochar effects on nutrient leaching (Major et al., 2009):

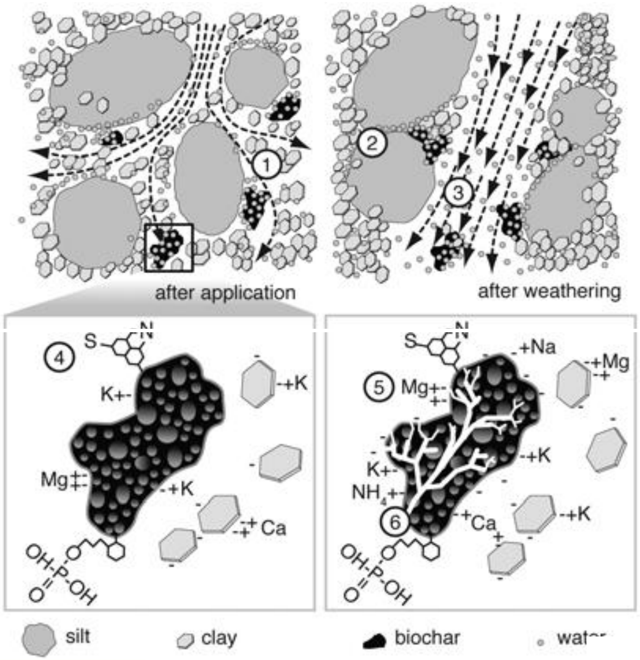
2. Nitrogen availability

Nutrient use efficiency

- CEC
- Water retention
- Microbial N immobilisation

Nutrient use efficiency (NUE) ↗

Leaching losses ↘

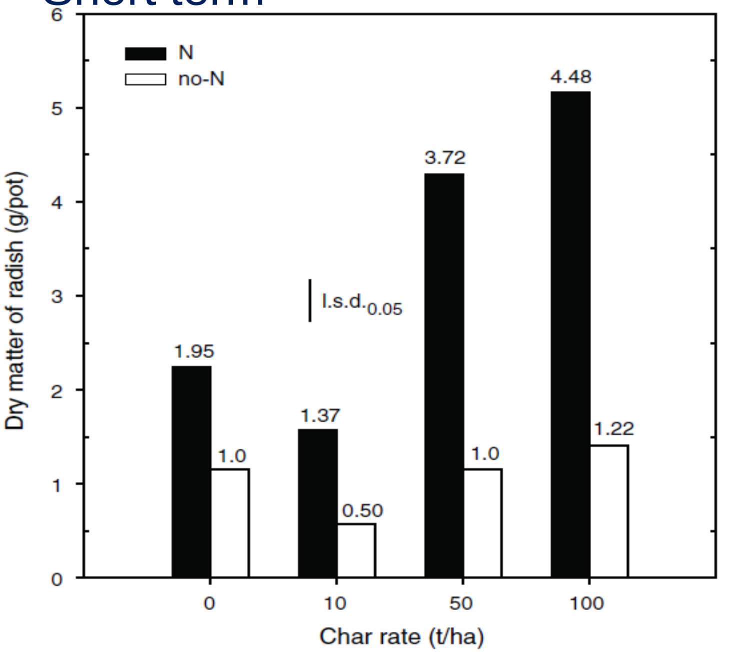


Schematic representation of proposed biochar effects on nutrient leaching (Major et al., 2009):

2. Nitrogen availability

Country	Year	Biochar	Dose t/ha	Crop	Soil	Type of experiment	Ref.
AUS	2007	Greenwaste	0, 10, 50	Radish	Sandy, low pH, OC and nutrients	Pot	Chan et al., 2007

Short term



Dry matter production of radish with and without nitrogen fertilizer as a function of rate of biochar.

100 kg N/ha applied

NUE ↗

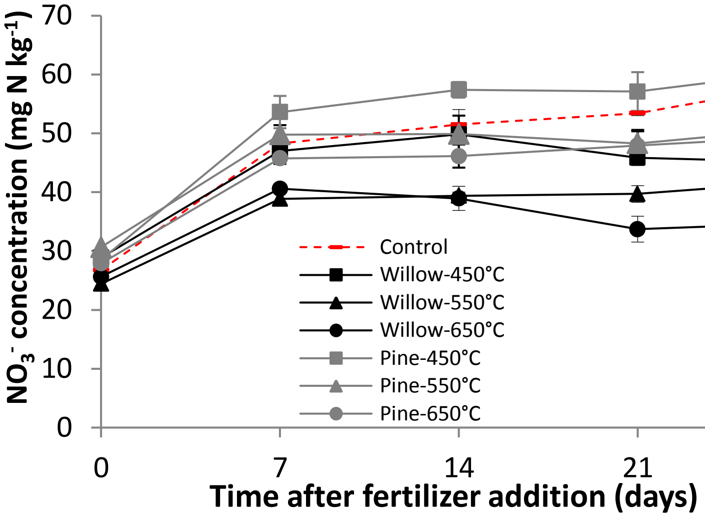
Table 3. Uptake of nutrients (g) by radish plants grown in biochar-amended soils at different rates and with and without N fertiliser
Within rows, means followed by the same letter are not significantly different ($P > 0.05$); *** $P < 0.001$

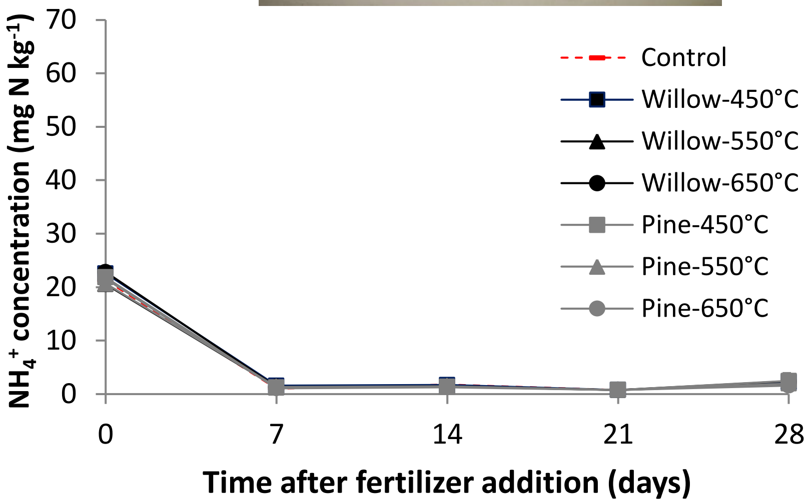
	Nil N				N				Significance level		
Biochar rate:	0	10	50	100 (t/ha)	0	10	50	100	Biochar rate	N	Biochar ×N
N	0.024e	0.015e	0.021e	0.027e	0.151c	0.098d	0.263b	0.323a	***	***	***
P	0.003de	0.002e	0.006c	0.009b	0.004d	0.002e	0.009b	0.016a	***	***	***
K	0.031cd	0.013d	0.039cd	0.052c	0.050c	0.041cd	0.168b	0.301a	***	***	***
Ca	0.015de	0.007e	0.019d	0.023d	0.033c	0.025d	0.059b	0.088a	***	***	***
Mg	0.004e	0.002f	0.004e	0.005cd	0.008c	0.006d	0.014b	0.019a	***	***	***

2. Nitrogen availability

Country	Year	Biochar	Dose t/ha	Crop	Soil	Type of experiment	Ref.
BE	2010	Willow/Pine	0, 40	/	Sandy loam, low OC	Incubation	Nelissen et al., submitted

Short term





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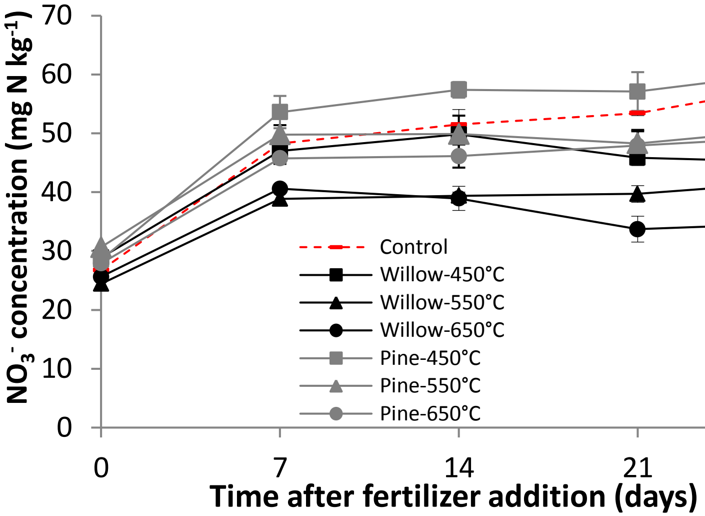
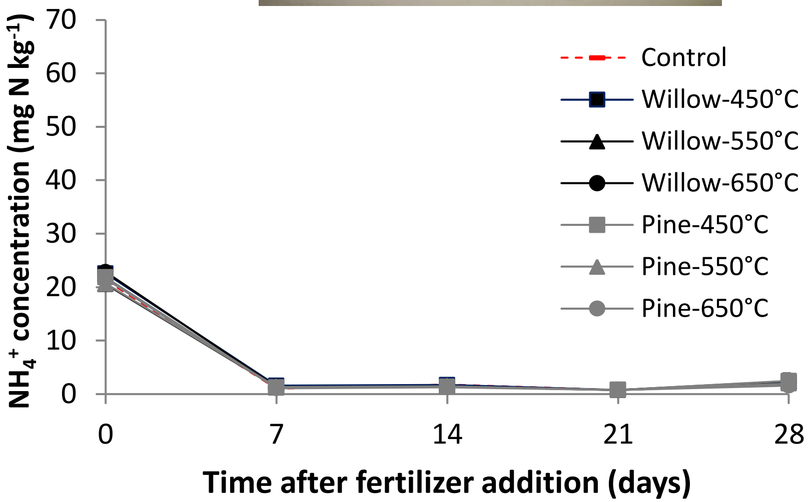




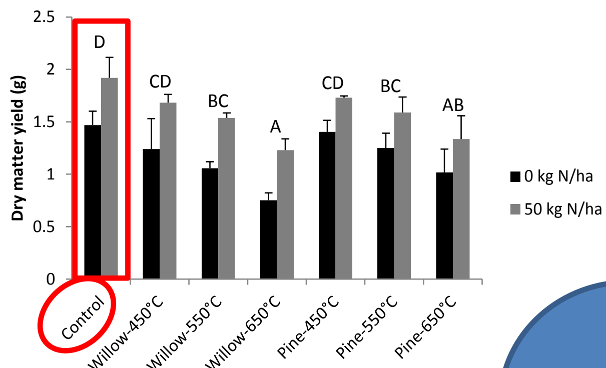
Nitrogen availability ↘

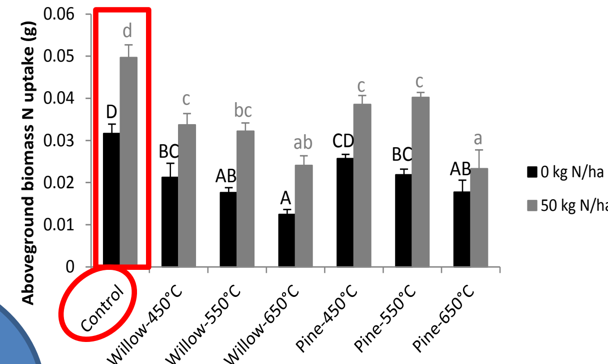
1. Incubation and pot experiment

Country	Year	Biochar	Dose t/ha	Crop	Soil	Type of experiment	Ref.
BE	2010	Willow/Pine	0, 40	Radish	Sandy loam, low OC	Pot	Nelissen et al., submitted

	Dry matter yield	*Aboveground biomass N uptake*

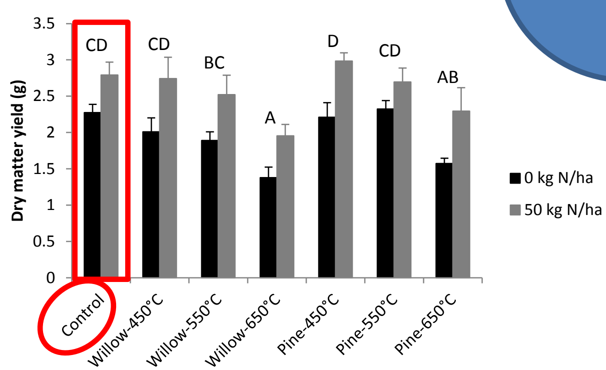
Radish

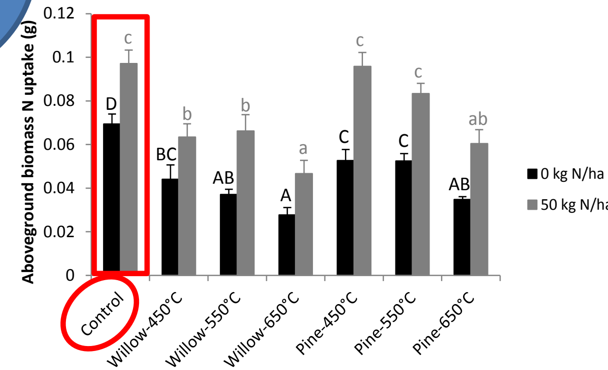




NUE ↘

Spring barley





2. Nitrogen availability

- Reduced soil NO_3^- availability ➔ (short-term) crop yield reduction
- Likely due to biotic N immobilization, N immobilization through biochar's micropores or stimulated NH_3 volatilization
- Effect biochar type dependent: yield increases as pyrolysis temperature decreases, but none of the biochar types performs better than the control
- Generally, biochar addition decreases the NUE
- Longer term effect?

2. Nitrogen availability

Biochar field experiment at ILVO

Objective

To investigate the effect of biochar application to a temperate agricultural soil on soil chemical, physical and biological properties, and on crop growth and quality under field circumstances.

Materials & Methods

- Biochar application in October 2011
- Biochar feedstock: mixture of hard- and softwood
- Biochar dose: 20 t ha^{-1}
- Plot size 7.5 x 12 m^2
- Crop grown: spring barley in both 2012 and 2013

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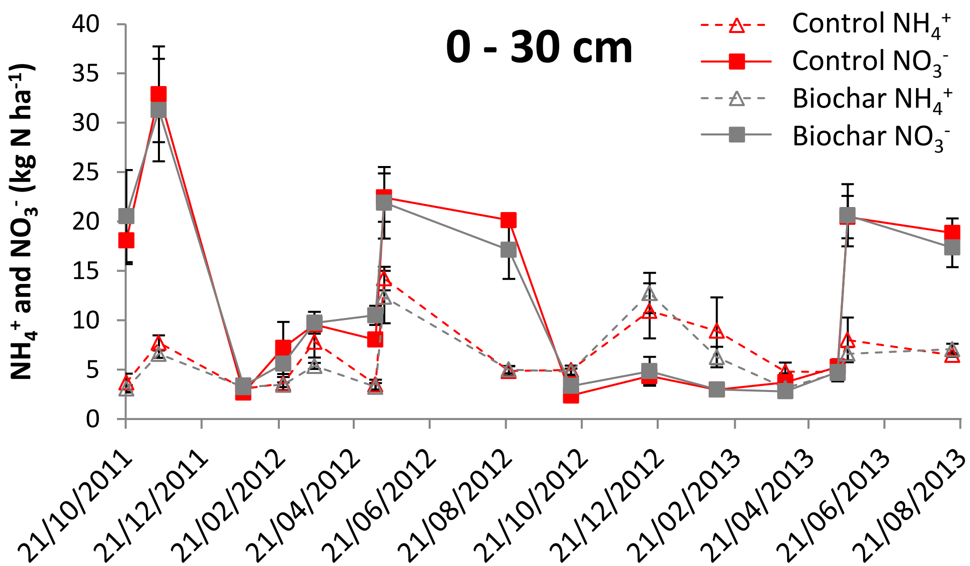
2. Nitrogen availability

Country	Year	Biochar	Dose t/ha	Crop	Soil	Type of experiment	Ref.
BE	2011-2013	Wood	0, 20	Spring barley	Sandy loam, low OC	Field	Nelissen et al., in preparation

Short + longer term



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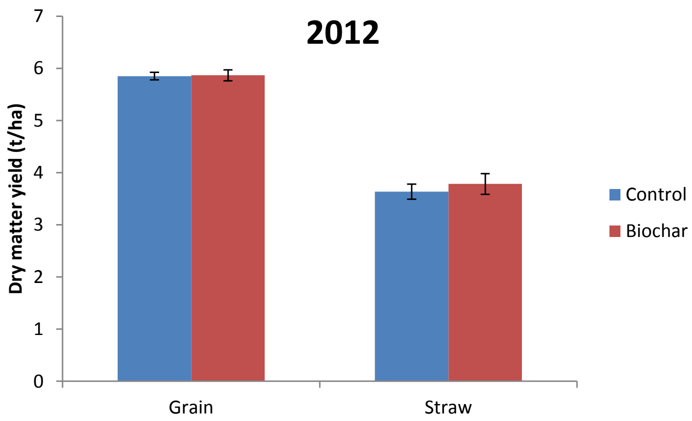
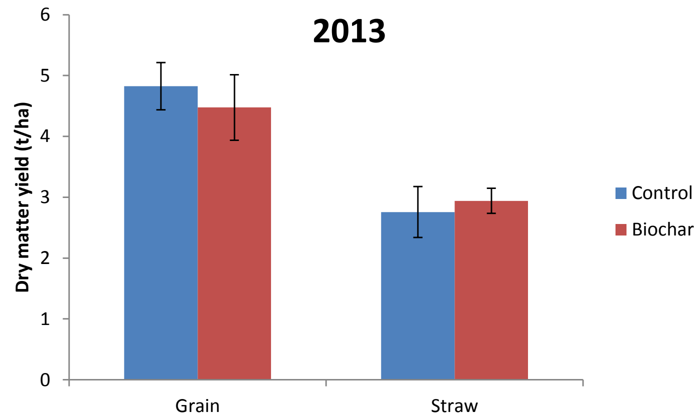
2. Nitrogen availability

Spring barley yield





2. Nitrogen availability

Conclusion

- Short term:
  - Direct effect (biochar feedstock e.g. manure)
  - Nitrogen immobilization:
    - Biotic (biochar feedstock e.g. wood, C:N > 20)
    - Abiotic
  - NUE

  } More fertilizer needed? Biochar application in autumn

  ➔ Effects biochar/soil type dependent
- Long term:
  - NUE could increase ➔ less fertilizer needed?

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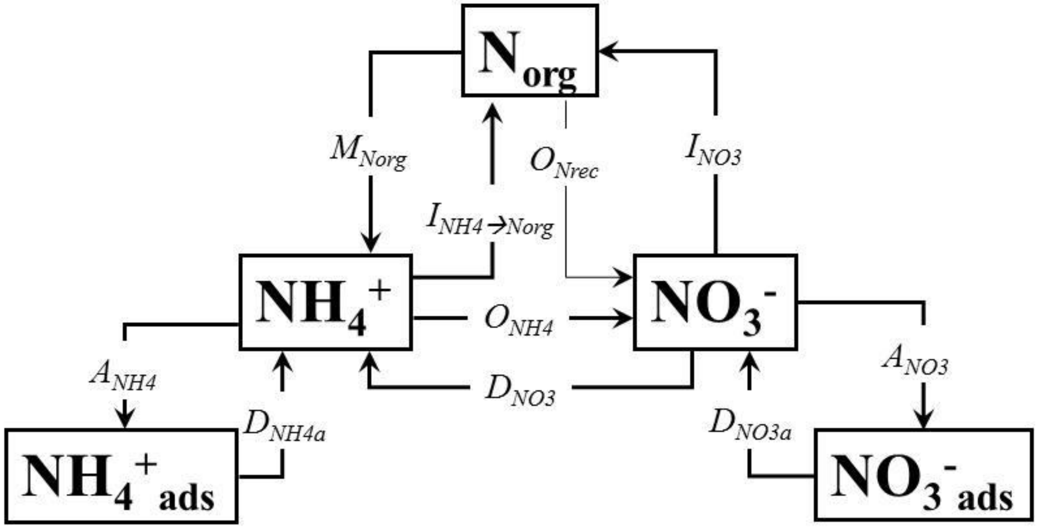
3. Nitrogen transformations in soil

Effects of biochar on soil N cycling: ^{15}N tracing experiments

To study effect of biochar on gross N transformation rates
➔ **^{15}N-tracing experiment**



3. Nitrogen transformations in soil

Biochar field experiment



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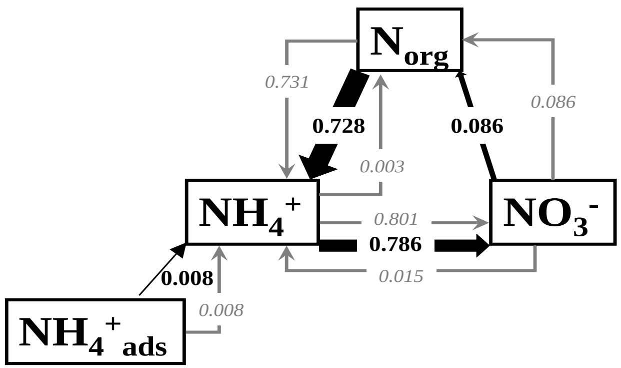
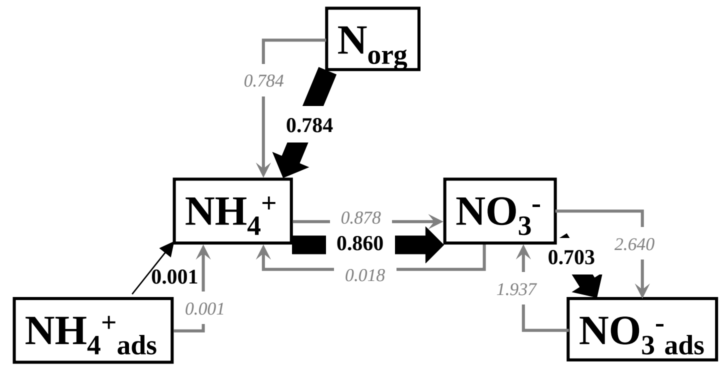
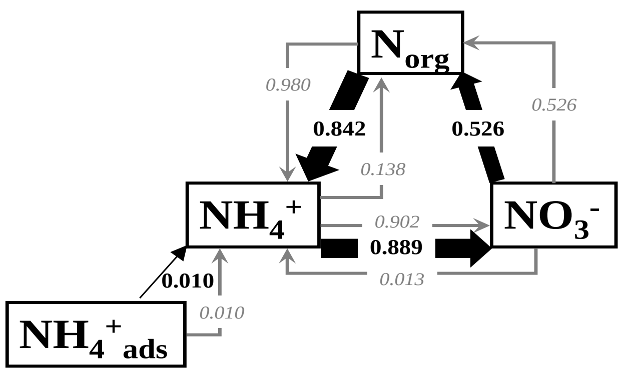
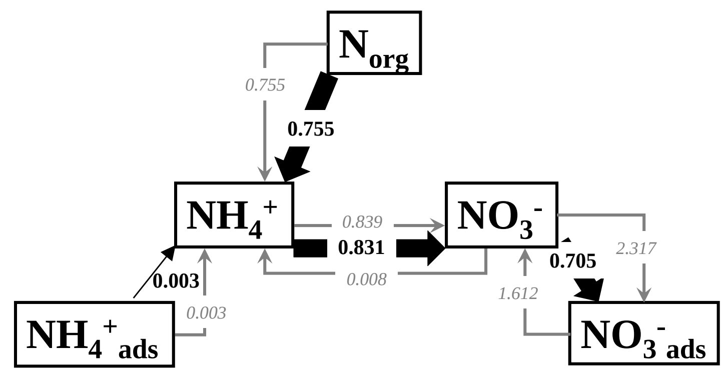
3. Nitrogen transformations in soil

Effects of biochar on soil N cycling: ^{15}N tracing experiments

	2011 (just after biochar application)	*2012 (1 year after biochar application)*
Control		
Biochar		

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3. Nitrogen transformations in soil

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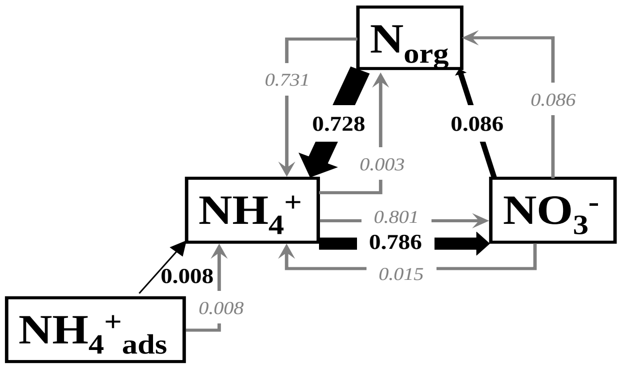
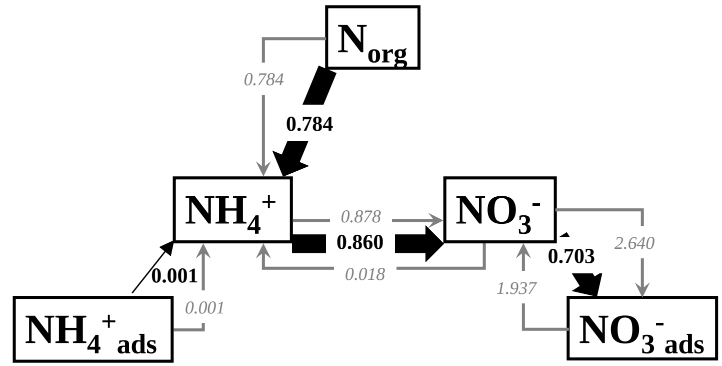
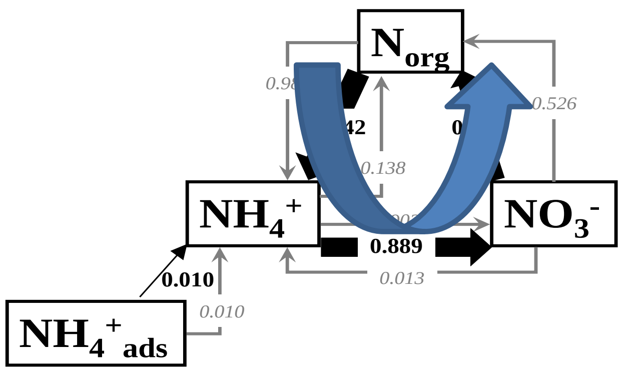
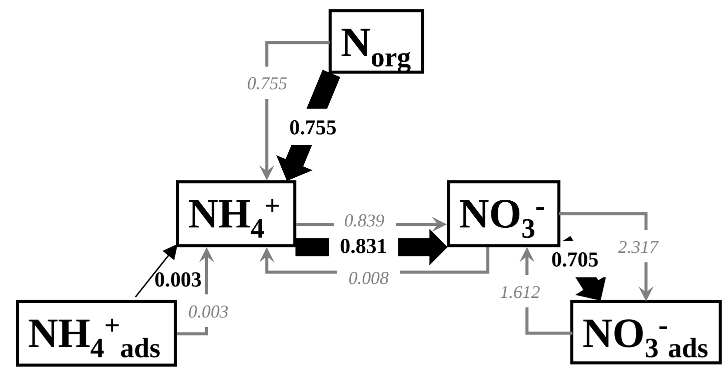
Control		
Biochar		

3. Nitrogen transformations in soil

Effects of biochar on soil N cycling: ^{15}N tracing experiments

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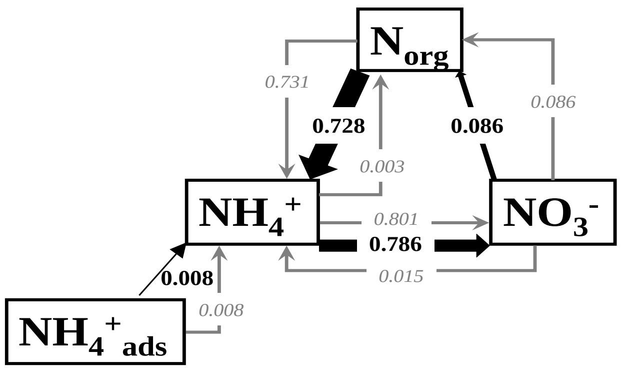

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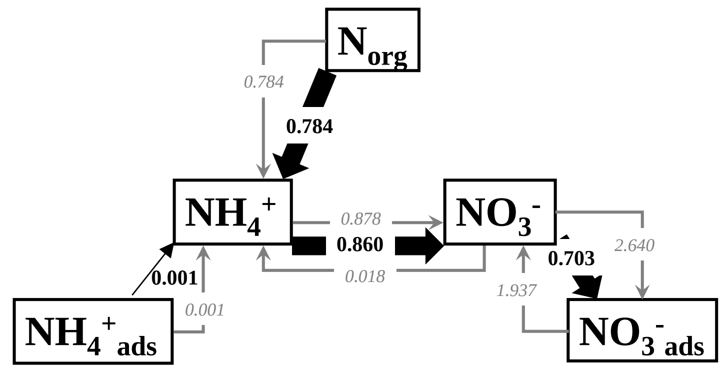

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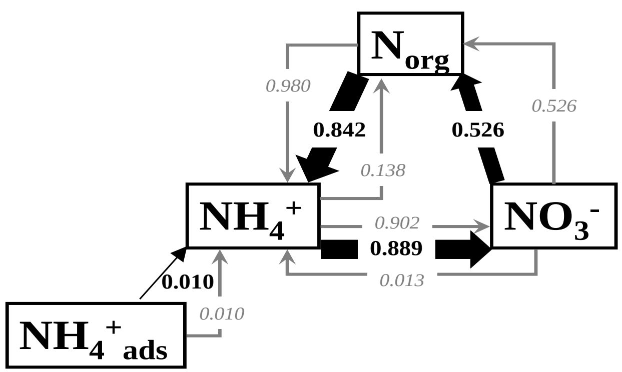

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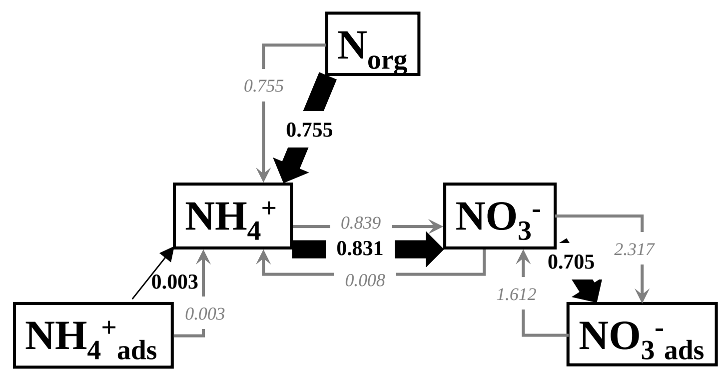

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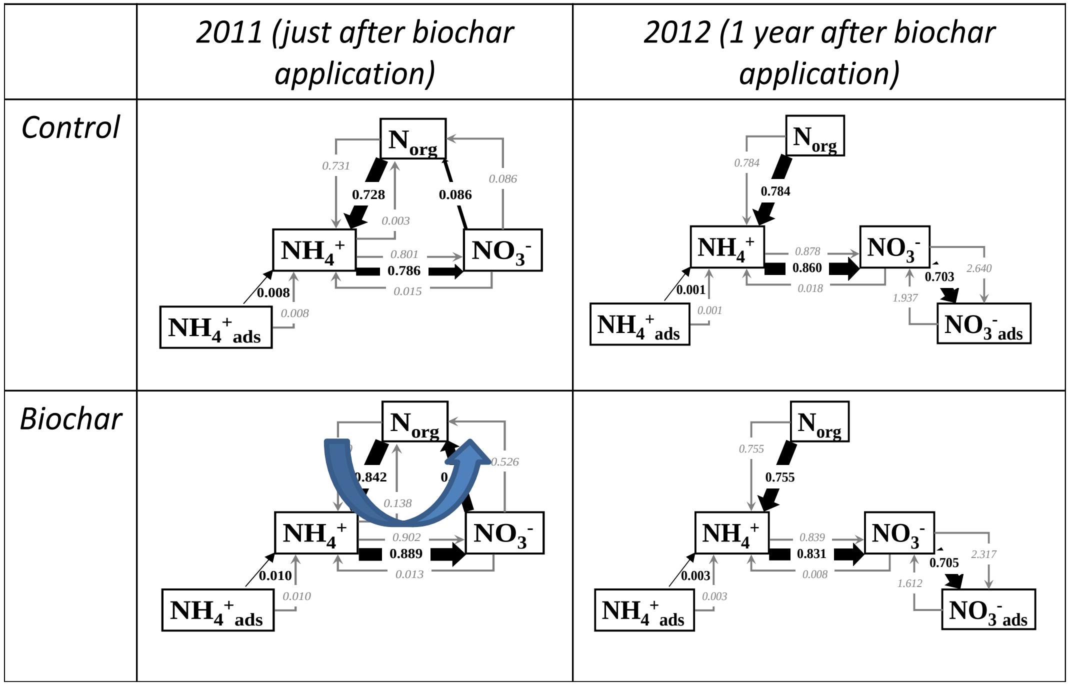
3. Nitrogen transformations in soil

Conclusion



- Short term: accelerated N-cycling, thereby increasing soil N bio-availability
- Longer term: biochar acts as an inert substance.

➔ Short-term effects are temporary

Overview

1. Nitrogen cycle
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4. **Greenhouse gas emissions**
5. Conclusions

4. Greenhouse gas emissions

Why studying N_2O and NO emissions?

N_2O: 298 times GWP of CO_2 over 100 years

NO: catalyzes tropospheric O_3

Sources?

Both anthropogenic and natural

➔ Soil biochemical processes: principal source of N oxides

<u>Nitrification</u>: $NH_4^+ \Rightarrow NO_2^- \Rightarrow NO_3^-$

<u>Denitrification:</u> $NO_3^- \Rightarrow NO_2^- \Rightarrow NO \Rightarrow N_2O \Rightarrow N_2$

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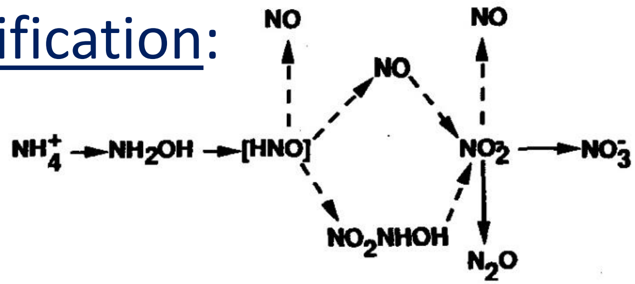
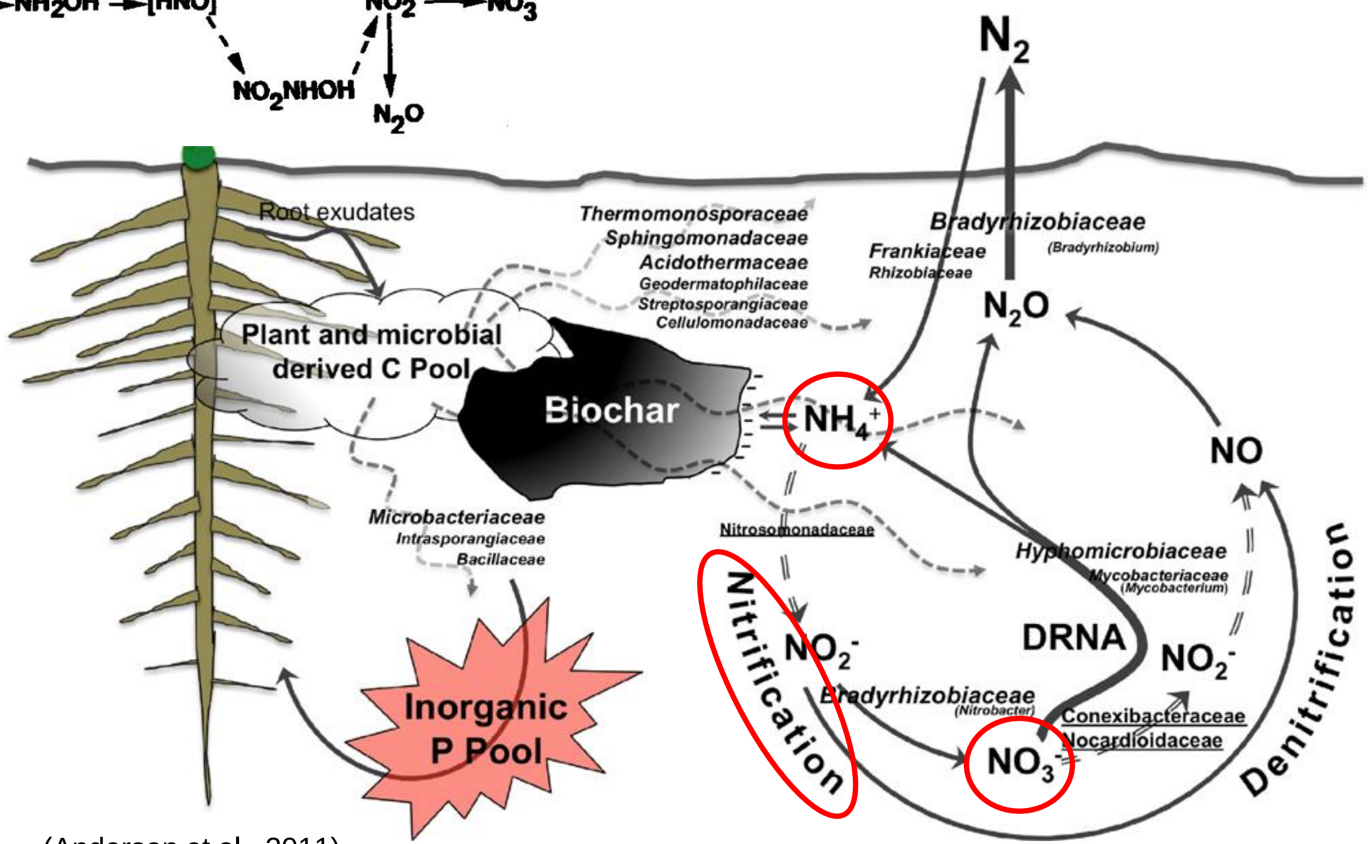
4. Greenhouse gas emissions

Nitrification:

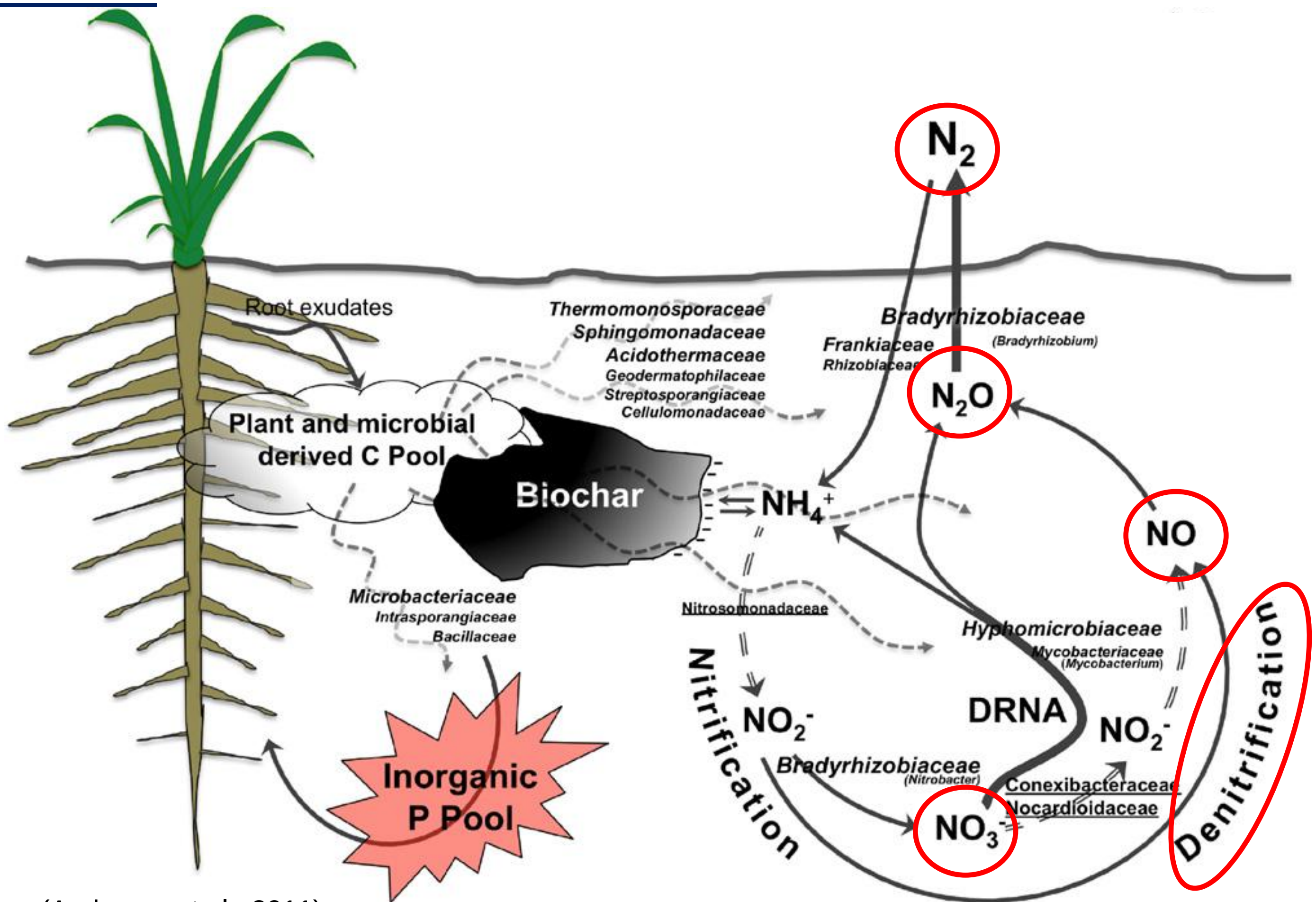




(Anderson et al., 2011)

4. Greenhouse gas emissions

Denitrification:



(Anderson et al., 2011)

4. Greenhouse gas emissions

N_2O emissions

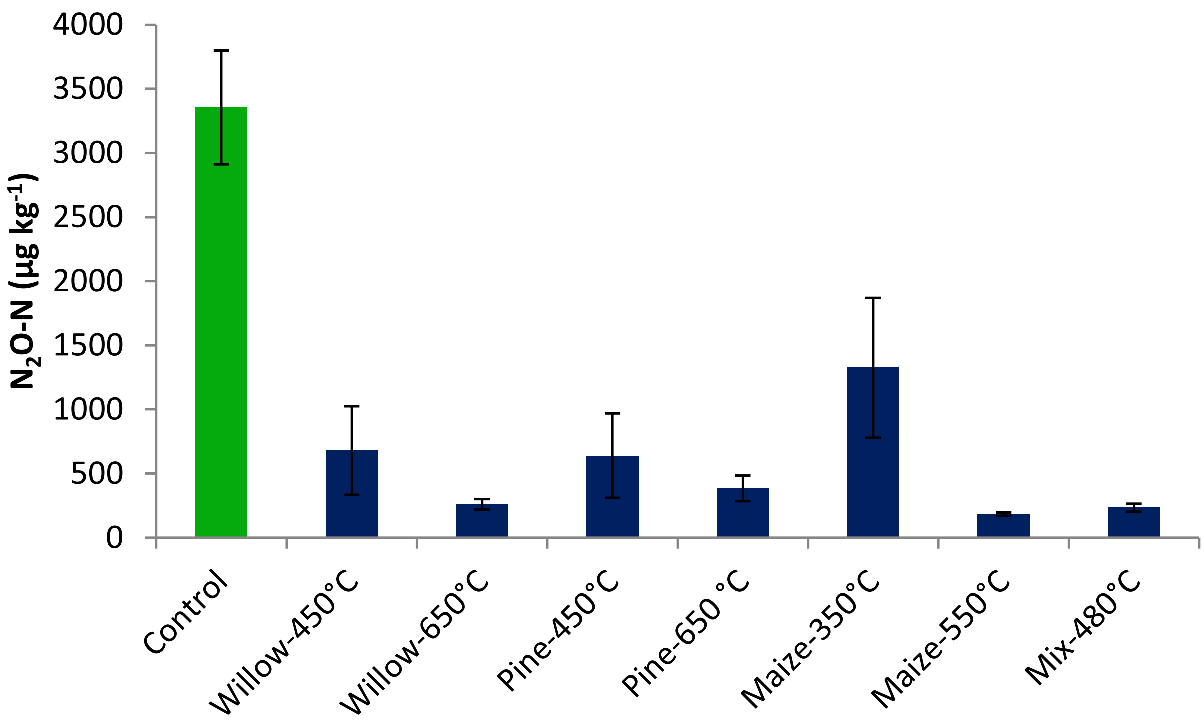
Dependent on:

- Soil water content (oxygen availability)
- N availability
- Soil pH
- Microbial community structure

➔ Biochar can affect these parameters

4. Greenhouse gas emissions

N_2O emissions



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4. Greenhouse gas emissions

Reference	Country	Soil type	Biochar feedstock	Pyrolysis temperature (°C)	Biochar dose (% w:w)	Fertilizer type	Fertilizer dose	Water content	Effect on N_2O emissions
				Incubation experiment					
Ameloot et al. (2013)	Belgium	Sandy loam	Wood Swine manure digestate	350 700	1.4	KNO_3	40 mg N kg^{-1}	70% WFPS	↘ 0
Augustenborg et al. (2012)*	Ireland	Typic Hapludalf Luvisol	Peanut hull Miscanthus	498 550	4	$(NH_4)_2SO_4$	0 kg ha^{-1} 100 kg ha^{-1}	50% WFPS	0
Bruun et al. (2011)	Denmark	Loamy	Wheat	525	1 - 3	Slurry	0 N ha^{-1} 150 kg N ha^{-1}	80% WFPS	 0
Case et al. (2012)	UK	Sandy loam	Hardwood	400	2 2 1 - 10	/	0	23% (w:w) After wetting event (28% w:w 78% WFPS	↘ 0 ↘
Cheng et al. (2012)	China	Black Chernozem	Wheat straw	450	0.3	NH_4NO_3	100 mg N kg^{-1}	60% WHC	0
Clough et al. (2010)	New Zealand	Silt loam	Pine	600	4	Urine	0 or 760 kg N ha^{-1}		
Kammann et al. (2012)	Germany	Luvisol	Various	Various	8	NH_4NO_3		65% WHC	
		Luvisol	Peanut hull	498	2 - 14	NH_4NO_3	50 mg N kg^{-1} after > 18 mo of incubation	80% WHC	(after fertilizer application)
Rogovska et al. (2011)	USA	Fine-loamy	Hardwood	450-500	0.5 - 2	Swine manure	0 or 5 g kg^{-1}	Field capacity	(11 mo after fertilizer ↘ application ↗)
Singh et al. (2010)	Australia	Alfisol Vertisol	Poultry manure Eucalyptus	400	0.76	N, P, K, glucose-C	**	Wetting-drying cycles	, 0 or
Spokas & Reicosky (2009)	USA	Silt loam	Various	Various	10	/	0	Field capacity	↘
Stewart et al. (2012)	USA	Various	Oak	550	1 - 20	/	0	60% WHC	
Troy et al. (2013)	Ireland	Acid brown earth	Pig manure digestate Sitka Spruce	600	0.80	Pig manure	0 170 kg N ha^{-1}	Start: 26% (w:w); leached twice weekly	0 ↘
van Zwieten et al. (2010)	Australia	Ferrosol	Various	Various	1 - 5	Urea 30 days after urea application	165 kg N ha^{-1}	65-70% WFPS 90-100% WFPS	↘ ↘
Yanai et al. (2007)	Japan	(Clay) loam	Municipal biowaste	700	8.2 2 - 8.2	/	0	73% WFPS 83% WFPS	↗
Zheng et al. (2012)	USA	Silt loam Loam	Oak	550	9	NH_4NO_3	0 or 100 kg N ha^{-1}	60% WHC	↘ 0 0 or
				Pot experiment					
Kammann et al. (2012)	Germany	Luvisol	Peanut hull	498	3 (50 t ha^{-1})	NH_4NO_3	100 kg N ha^{-1} (+ extra N at end of experiment)	Pots slowly watered until water emerged at the pot bottom	↘
				Field experiment					
Case et al. (2013)	UK	Sandy loam	Hardwood	400	3.2 (49 t ha^{-1})	/	0	Field conditions	0
Castaldi et al. (2011)	Italy	Silty loam	Hardwood	500	1.6 - 3.3 (30 - 60 t ha^{-1})	N, P	**	Field conditions	, 0 or
Karhu et al. (2011)	Finland	Silt loam	Birch	400	0.4 (9 t ha^{-1})	Green manure		Field conditions	0
Scheer et al. (2011)	Australia	Ferrosol	Cattle feedlot waste	550	1 (10 t ha^{-1})	N, P, K	**	Field conditions	, 0 or
Suddick & Six (2013)	USA	Silt loam	Walnut shells	900	0.5 (5 + 5 t ha^{-1})	N, cover crop	**	Field conditions	0
Taghizadeh-Toosi (2011)	New Zealand	Silt loam	Pine	350	1.2 (15 t ha^{-1}) 2.4 (30 t ha^{-1})	Urine + urea	930 kg N ha^{-1}	Field conditions	0
Zhang et al. (2012)	China	Loamy	Wheat straw	350-550	0.9 - 1.8 (20 - 40 t ha^{-1})	Urea	0 300 kg N ha^{-1}	Field conditions	0

4. Greenhouse gas emissions

Effect on NO emissions

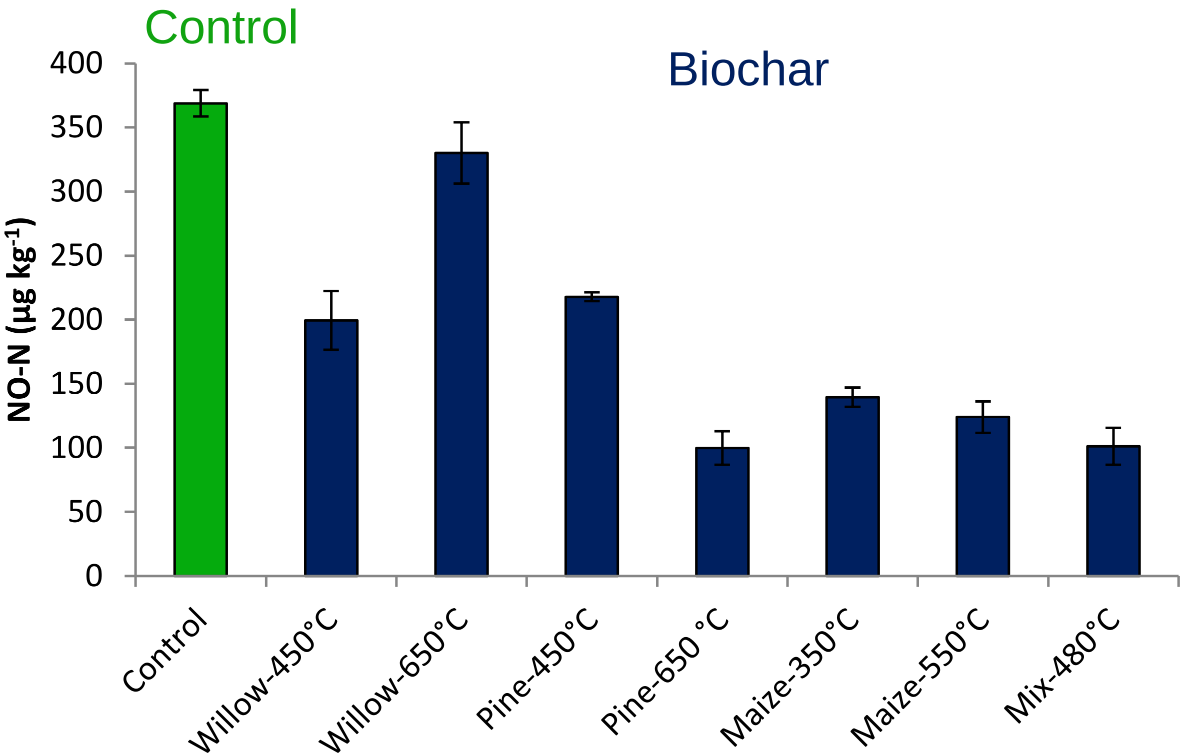
Dependent on:

- N availability
- Soil pH

➔ Biochar can affect these parameters

4. Greenhouse gas emissions

NO emissions



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4. Greenhouse gas emissions

Conclusion

- Biochar has potential to reduce N_2O and NO emissions after fertilizer application (at least in the short term)
- Emission reduction likely due to reduced substrate availability for (de)nitrification due to:
  - Biotic N immobilization
  - N immobilization through biochar's micropores
  - Stimulated NH_3 emissions

Other possible mechanisms for N_2O emission decrease:

1) pH increase → N_2O:N_2 ratio decreased
2) N_2O sorption
3) Increased aeration
4) Microbial inhibiting compounds present in biochar

Overview

1. Nitrogen cycle
2. Nitrogen availability
3. Nitrogen transformations in soil
4. Greenhouse gas emissions
5. **Conclusions**

5. Conclusions

Short-term:

- Mixed effects observed of biochar on N availability and NUE ➔ effects change depending on biochar/soil type
- Accelerated N cycling

Long-term effect?

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Thank you for your attention!