Recovery from N saturation in Flemish forests under high N deposition

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3rd ICP Forests Scientific Conference - 2014

26 - 28 May 2014, Athens, Greece

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I will present

- **Introduction – N saturation and recovery**
- **Objectives of this study**
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  - Data handling
  - Statistical analysis
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  - pH
  - NO_3^- leaching
  - N retention
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Introduction – N saturation and recovery

Temperate forest ecosystems

- During the past decades elevated nitrogen (N) + sulphur (S) deposition caused N saturation and acidification of temperate forests in Europe and North America.

  (e.g. Aber et al., 1989; Lorenz & Granke, 2009)

- Thanks to emission reduction, depositions stabilized or decreased in many areas. In European forests (2000-2010):
  - S: ↘↘ 6% y^{-1}
  - N: ↘ 2% y^{-1}

  (Waldner et al., in press)

- Recently, several studies reported initial chemical recovery in the soil compartment, which was indicated by:

  ↘ NO_3^- leaching
  ↗ pH
  ↗ mobilization of accumulated organic C and N stocks

  (e.g. Vanguelova et al., 2010; Oulehle et al., 2011)

Flanders, northern Belgium

Decline of depositions is reflected in soil solution

In 1994, acidifying depositions (throughfall + stemflow) at intensive forest monitoring plots were high : 42 kg inorganic N ha^{-1} y^{-1} and 27 kg S ha^{-1} y^{-1}.

Trend analysis confirmed a decrease thereafter (1994-2010):

- SO_4^{2-}: ↘ 5-6% y^{-1} (100% of plots)
- NH_4^+: ↘ 3-5% y^{-1} (100% of plots)
- NO_3^-: ↘ 1-2% y^{-1} (60% of plots)

Simultaneously, soil solution fluxes of NO_3^-, SO_4^{2-} and Al ↘

But critical loads/levels were still exceeded in 2010.

(Verstraeten et al., 2012)

Dissolved organic carbon (DOC) concentrations and fluxes increased in soil solution (2002-2012):

- DOC concentrations: ↗ 3-7% y^{-1} (100% of plots)
- DOC fluxes: ↗ 5-6% y^{-1} (40% of plots)

(results for deeper mineral soil)

(Verstraeten et al., 2014)

Objectives of this study

The main objective of the present study was to give a more complete answer to this question:

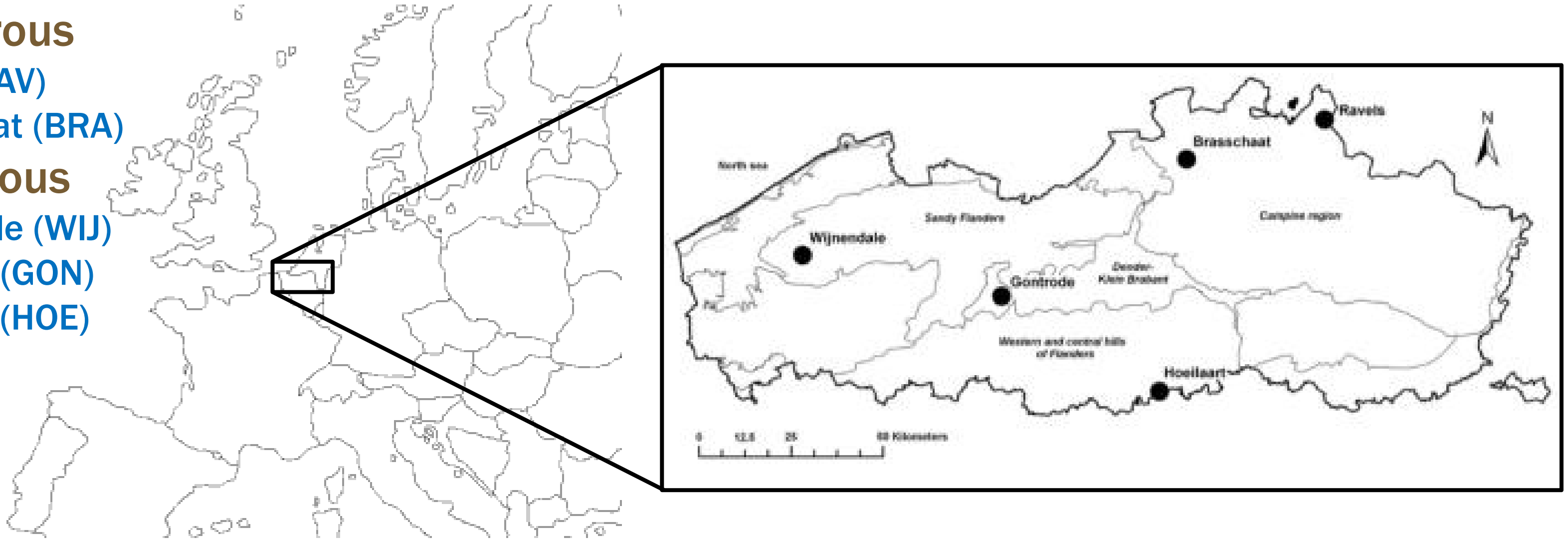
- Is the N status of Flemish forests improving?

Materials and Methods

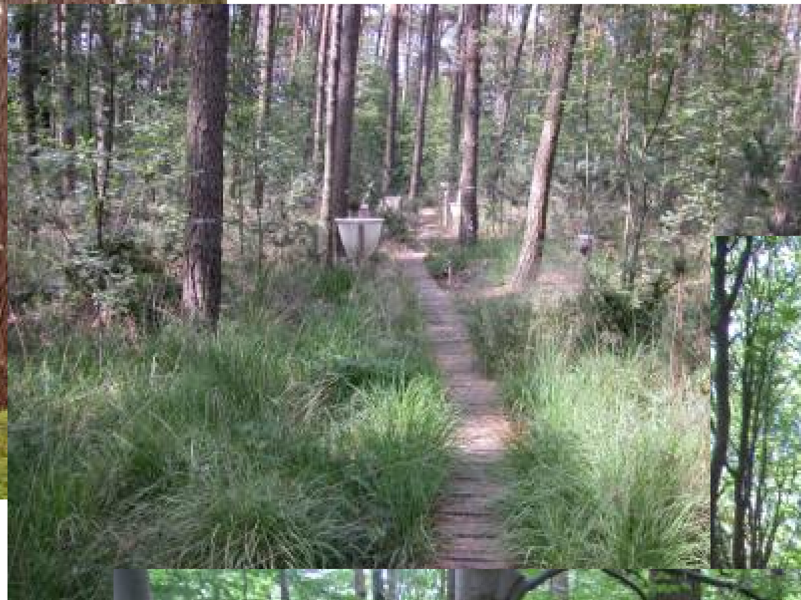
Study area

Data from 5 ICP Forests intensive monitoring plots were selected:

- 2 coniferous
  - Ravels (RAV)
  - Brasschaat (BRA)
- 3 deciduous
  - Wijnendale (WIJ)
  - Gontrode (GON)
  - Hoeilaart (HOE)

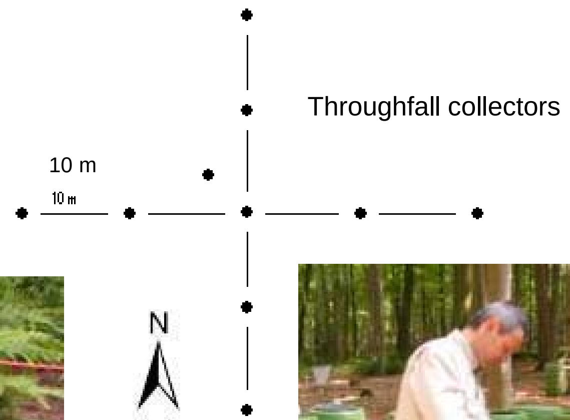


Plot	Coordinates		Elevation	Temperature	Precipitation	Tree species	Age	Former land use	Basal area	Throughfall	Stemflow
	N	E	m	°C	mm		years		m²/ha	%	%
Coniferous forests											
RAV	51°24'07"	05°03'15"	35	10.4	887	*Pinus nigra subsp. laricio*	80	heath	44.9	68.3	-
BRA	51°18'28"	04°31'11"	14	10.8	882	*Pinus sylvestris*	81	heath	29.2	78.6	-
Deciduous forests											
WIJ	51°04'11"	03°02'14"	31	11.0	867	*Fagus sylvatica*	75	arable	36.5	62.0	14.7
GON	50°58'31"	03°48'15"	26	10.6	786	*Quercus robur, Fagus sylvatica*	92	old growth	31.9	71.8	3.2
HOE	50°44'45"	04°24'47"	129	10.7	854	*Fagus sylvatica*	101	old growth	28.9	70.9	5.8



Sample collection

- 1994-2013
- 2 times per month
- 4 open field precipitation collectors
- 10 throughfall collectors
- 3-5 stemflow collectors (beech)
- soil solution:
  - organic layer (4-6 zero-tension lysimeters)
  - mineral soil (3 locations, 2-4 suction cup lysimeters per depth)
    - topsoil
    - subsoil
    - deeper mineral soil



Chemical analysis

on 500 ml composite subsamples of each fraction

1994-2013:

- pH (potentiometric, WTW multi 340i)
- NH_4^+, NO_3^- and NO_2^- concentrations (ion chromatography)

2005-2013:

- Total N concentrations (continuous flow method, Skalar)

Data handling

- **Dissolved organic nitrogen:** DON = Total N – (NH_4^+-N + NO_3^--N + NO_2^--N)
- N fluxes = water fluxes * concentrations
- Stand deposition = throughfall + stemflow
- Soil water fluxes were calculated using Na^+ as a "tracer ion" for each soil depth (Bailey et al., 2003)
- DIN:DON = (NH_4^+-N + NO_3^--N + NO_2^--N) * DON^{-1}
  Was proposed as an indicator to detect changes in ecosystem N status
  Assumption: DON export is not related to N input
  (Williams et al., 2004)

N status	DIN:DON
0	<0.5
1	0.5-2.0
2	>2.0

Williams, M.W., Clow, D., Blett, T., 2004. A Novel Indicator of Ecosystem N Status: DIN to DON Ratio in Riverine Waters. American Geophysical Union, Fall Meeting 2004, abstract #H53F-05.

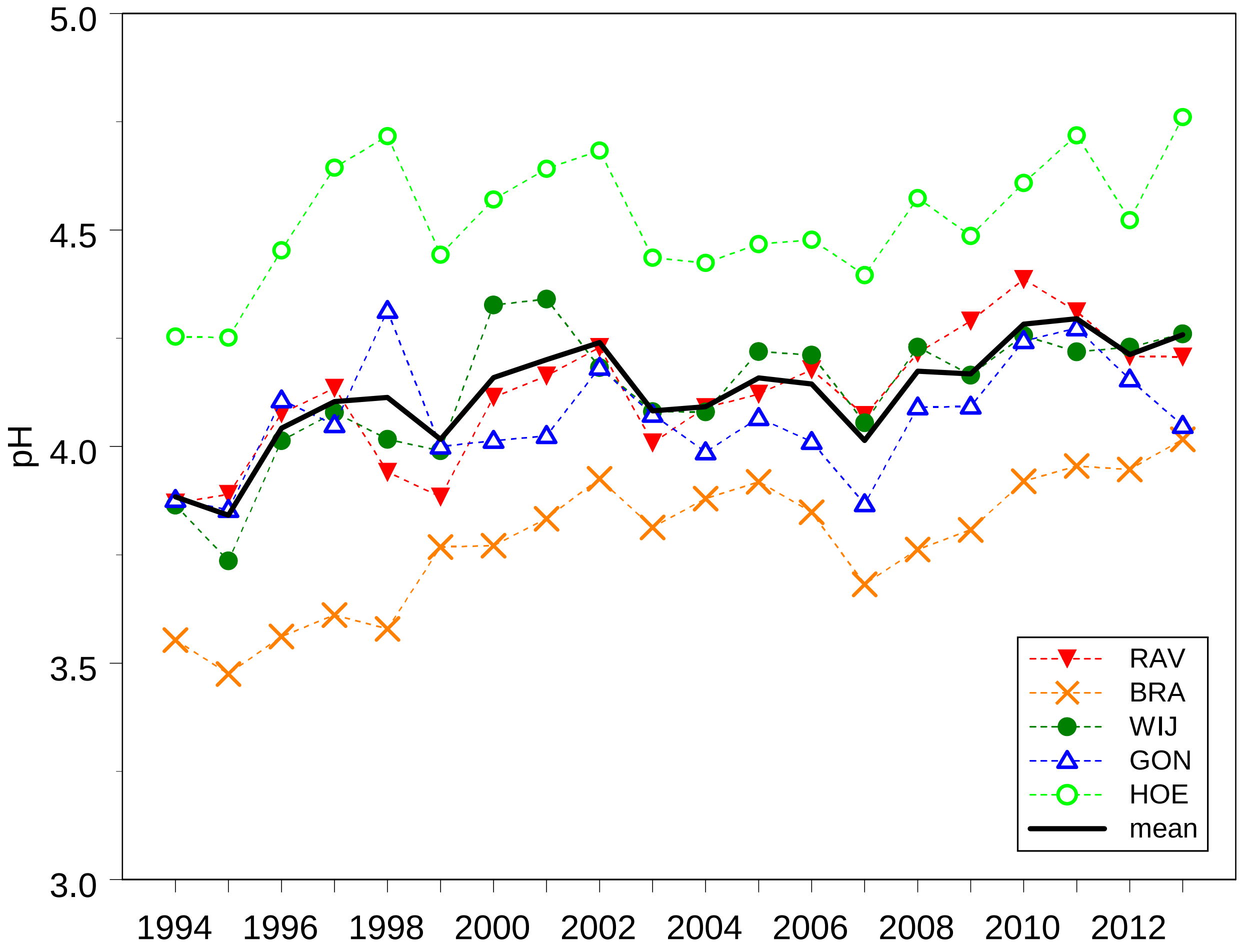
Statistical analysis

- *Trend analysis*
  - Mann-Kendall test (MK) (Mann, 1945; Helsel & Hirsch, 2002)
  - Seasonal Mann-Kendall test (SMK) (Hirsch et al., 1982; Hirsch & Slack, 1984)
  estimated following Sen (Sen, 1968)

- *Linear regression*

Results

pH in the deeper mineral soil (1994-2013)



Trend (SMK)

Plot	Mean	Slope
RAV	4.14	0.016***
BRA	3.79	0.020***
WIJ	4.14	0.016***
GON	4.07	0.008***
HOE	4.54	0.007*

Overall ↗, on average 0.015 pH units y^{-1}.

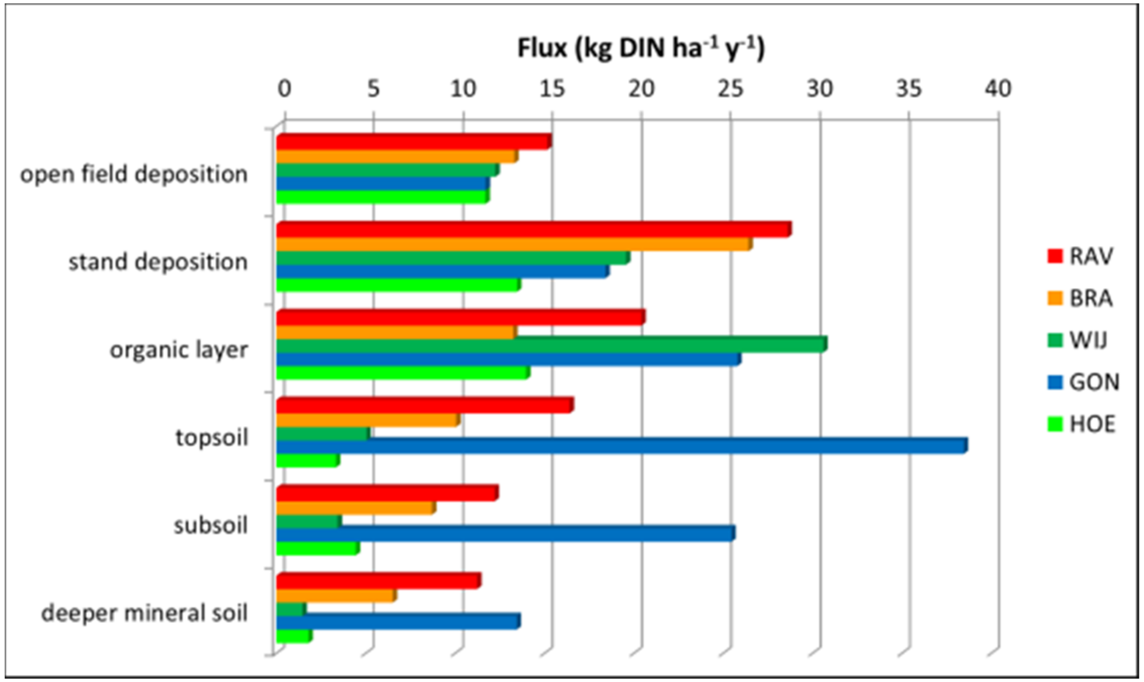
Mean annual N fluxes (2005-2013)

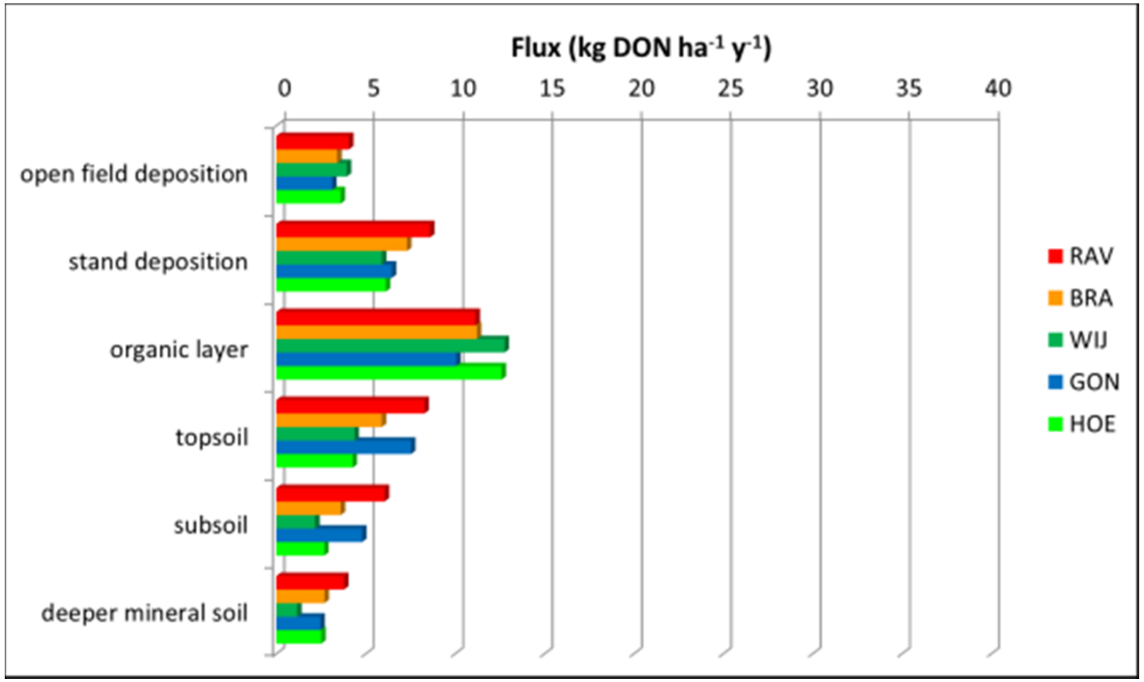
DIN

- **deposition**
  coniferous > deciduous
  (pollution climate)
- **soil solution**
  considerable differences between plots

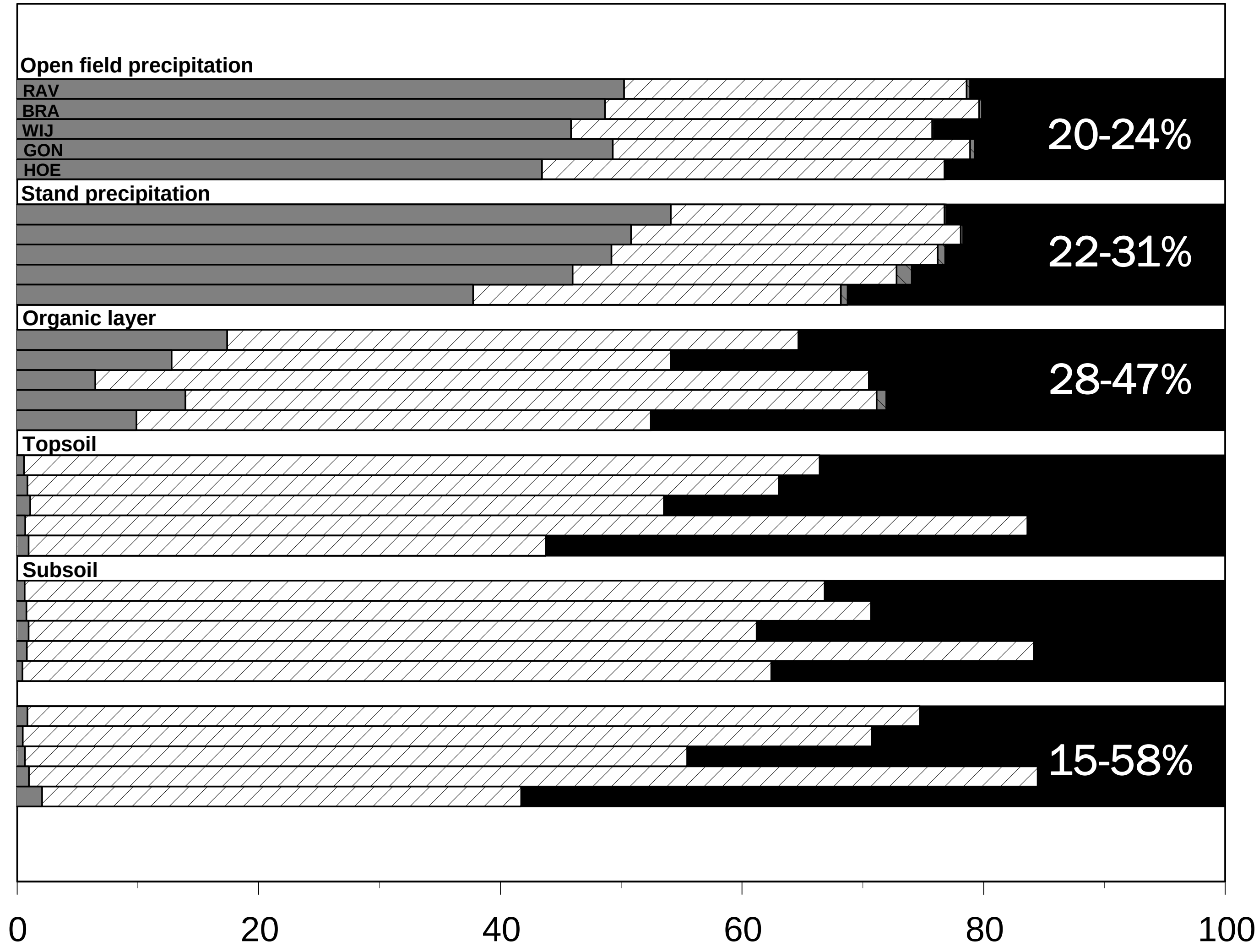
DON

- **deposition**
  3-4 kg ha^{-1} y^{-1} DON in open field, elevated:
  <1-2 kg ha^{-1} y^{-1} in unpolluted areas
  (e.g. Mustajärvi et al., 2008)
- **soil solution**
  highest in organic layer (litter and SOM decomposition)
  declines with depth (adsorption and uptake)
  1-4 kg ha^{-1} y^{-1} DON leaching





Composition of N fluxes (%) (2005-2013)

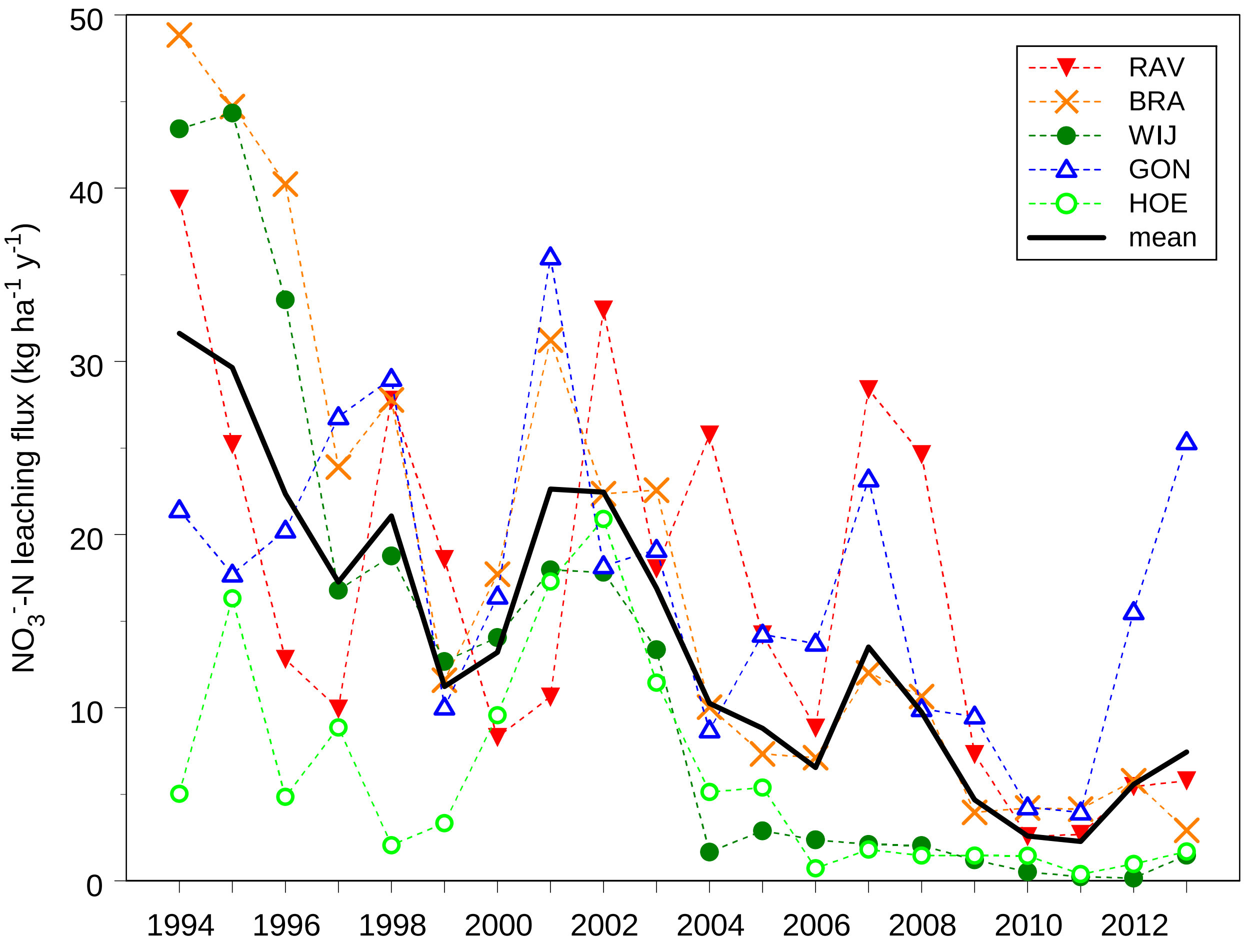


Mean flux of NH_4^+-N (grey bars), NO_3^--N (white dashed bars), NO_2^--N (grey dashed bars) and DON (black bars) shown as % of Total N flux.

NH_4^+-N dominates deposition; nearly absent in mineral soil
NO_3^--N dominates in mineral soil
NO_2^--N negligible
%DON ±constant in deposition; considerable variation in soil solution

NO_3^-- leaching (1994-2013)

Flux of NO_3-N (kg N ha^{-1} y^{-1}) in the deeper mineral soil



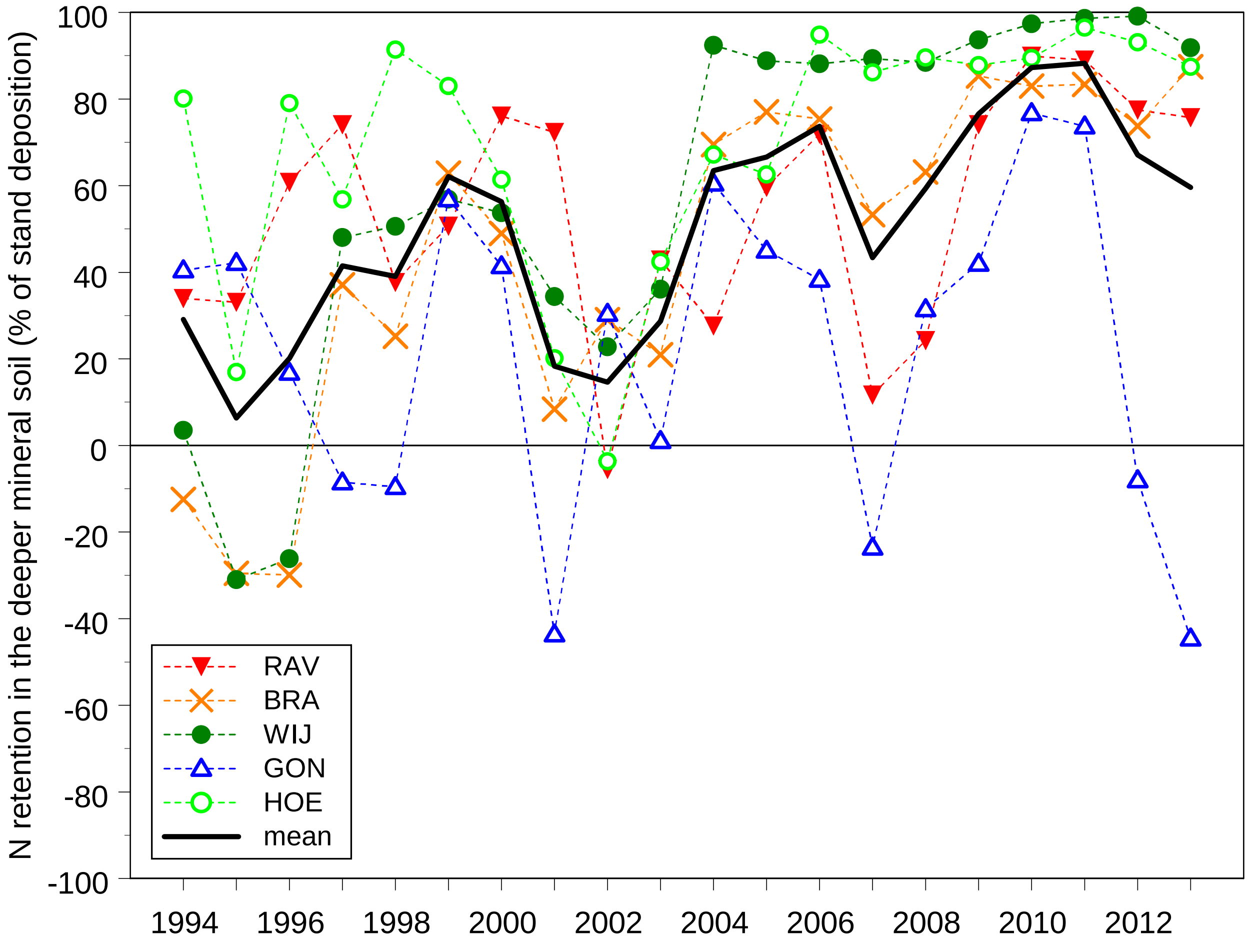
Trend (SMK)

Plot	Mean	Slope
RAV	16.45	-0.70***
BRA	17.95	-1.27***
WIJ	12.37	-1.06***
GON	17.16	-0.44***
HOE	6.01	-0.25***

Overall ↘ , on average 0.75 kg N ha^{-1} y^{-1}.
NO_3^- leaching nearly halted quite suddenly in WIJ (2004) and HOE (2006).
A sudden halt of NO_3^- leaching was also observed by Oulehle et al. (2011).

N Retention (1994-2013)

$100 - (NO_3^- \text{-N flux deeper mineral soil}) / (NO_3^- \text{-N} + NH_4^+ \text{-N stand deposition}) * 100$



Trend (SMK)

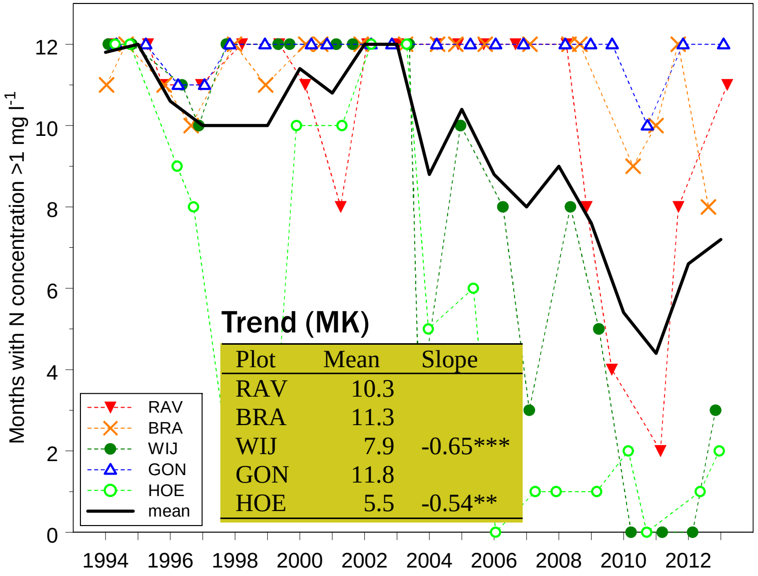
Plot	Mean	Slope
RAV	53.81	1.48***
BRA	41.17	3.25***
WIJ	57.78	3.63***
GON	16.59	
HOE	63.16	1.33***

Overall ↗ except in GON (high NO_3^- exports particularly in years with spring drought and autumn wetness).

Critical limits: number of months with exceedance in the deeper mineral soil (1994-2013)

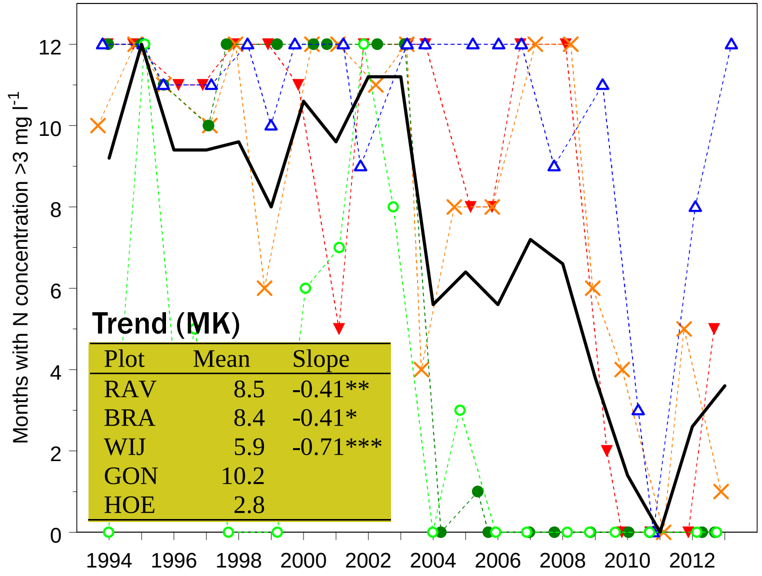
(EEC, 1991; Sverdrup and Warfvinge ,1993; UNECE, 2007)

Elevated N leaching/N saturation (>1 mg N l^{-1})



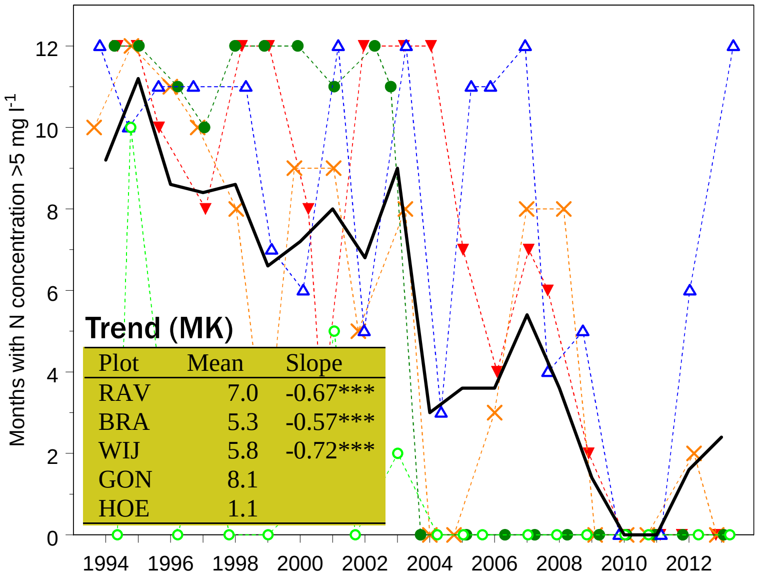
Plot	Mean	Slope
RAV	10.3	
BRA	11.3	
WIJ	7.9	-0.65***
GON	11.8	
HOE	5.5	-0.54**

Reduced fine root biomass/root length (>3 mg N l^{-1})



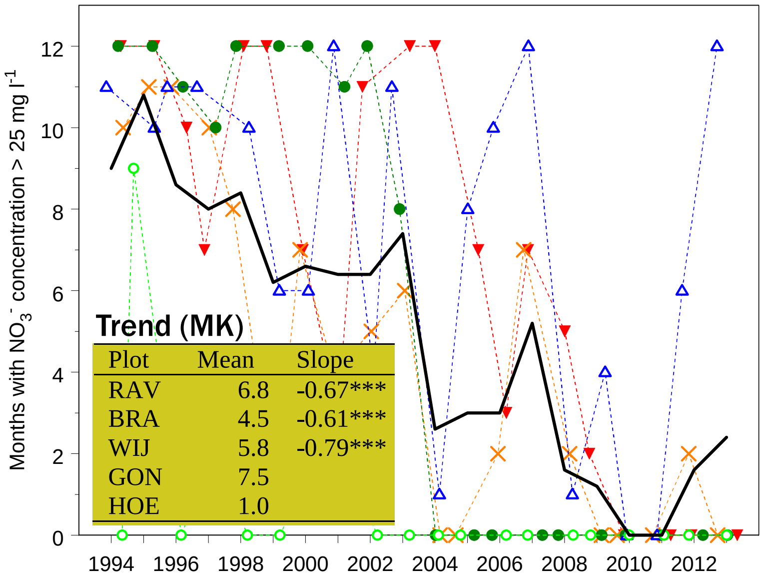
Plot	Mean	Slope
RAV	8.5	-0.41**
BRA	8.4	-0.41*
WIJ	5.9	-0.71***
GON	10.2	
HOE	2.8	

Enhanced sensitivity to frost and fungi (> 5 mg N l^{-1})



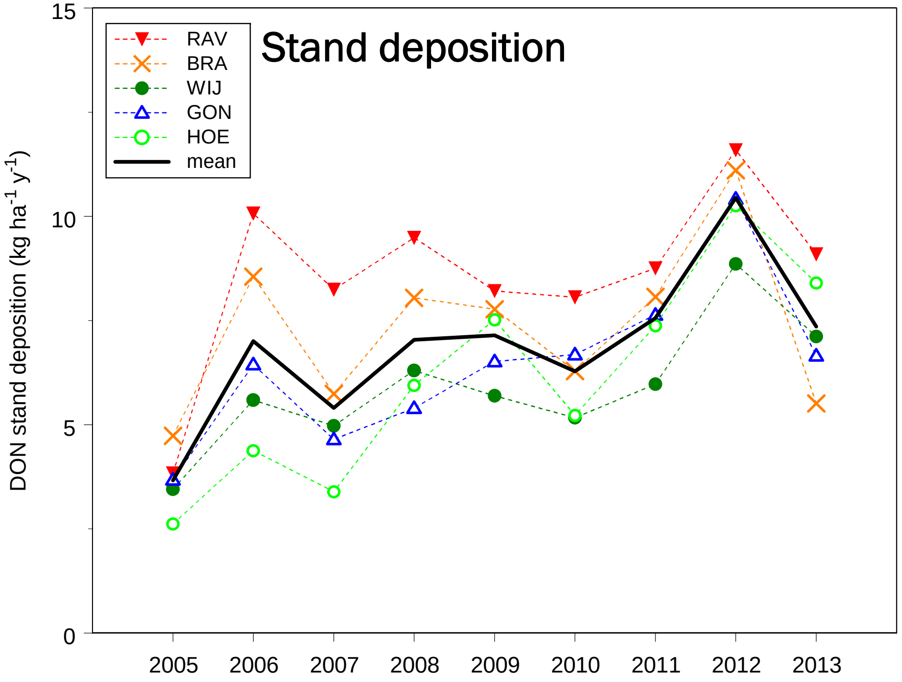
Plot	Mean	Slope
RAV	7.0	-0.67***
BRA	5.3	-0.57***
WIJ	5.8	-0.72***
GON	8.1	
HOE	1.1	

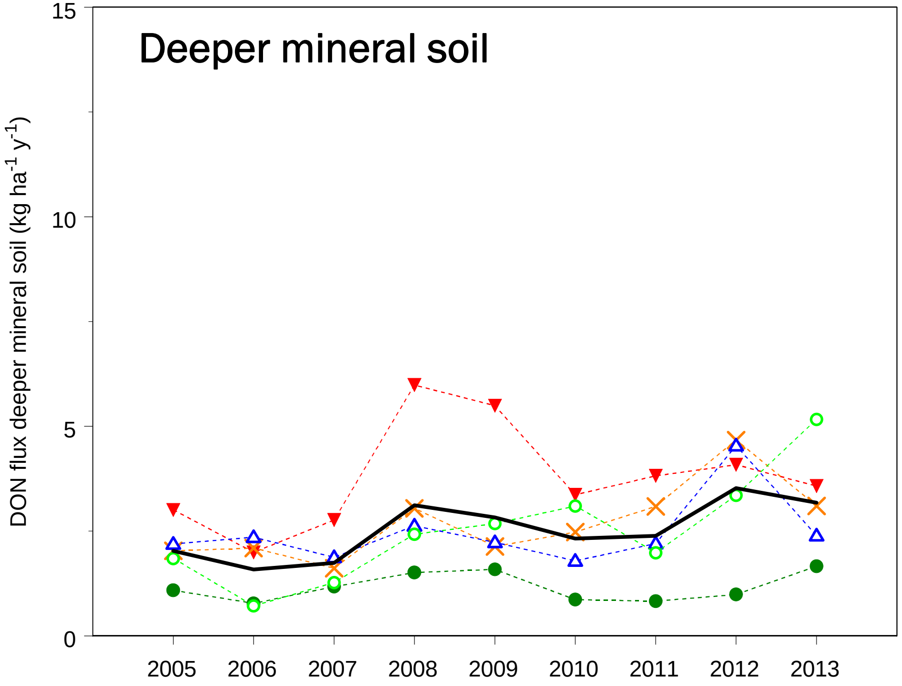
Guide value drinking water directive (>25 mg NO_3^- l^{-1})



Plot	Mean	Slope
RAV	6.8	-0.67***
BRA	4.5	-0.61***
WIJ	5.8	-0.79***
GON	7.5	
HOE	1.0	

DON – trend analysis (2005-2013)





Trend (SMK)

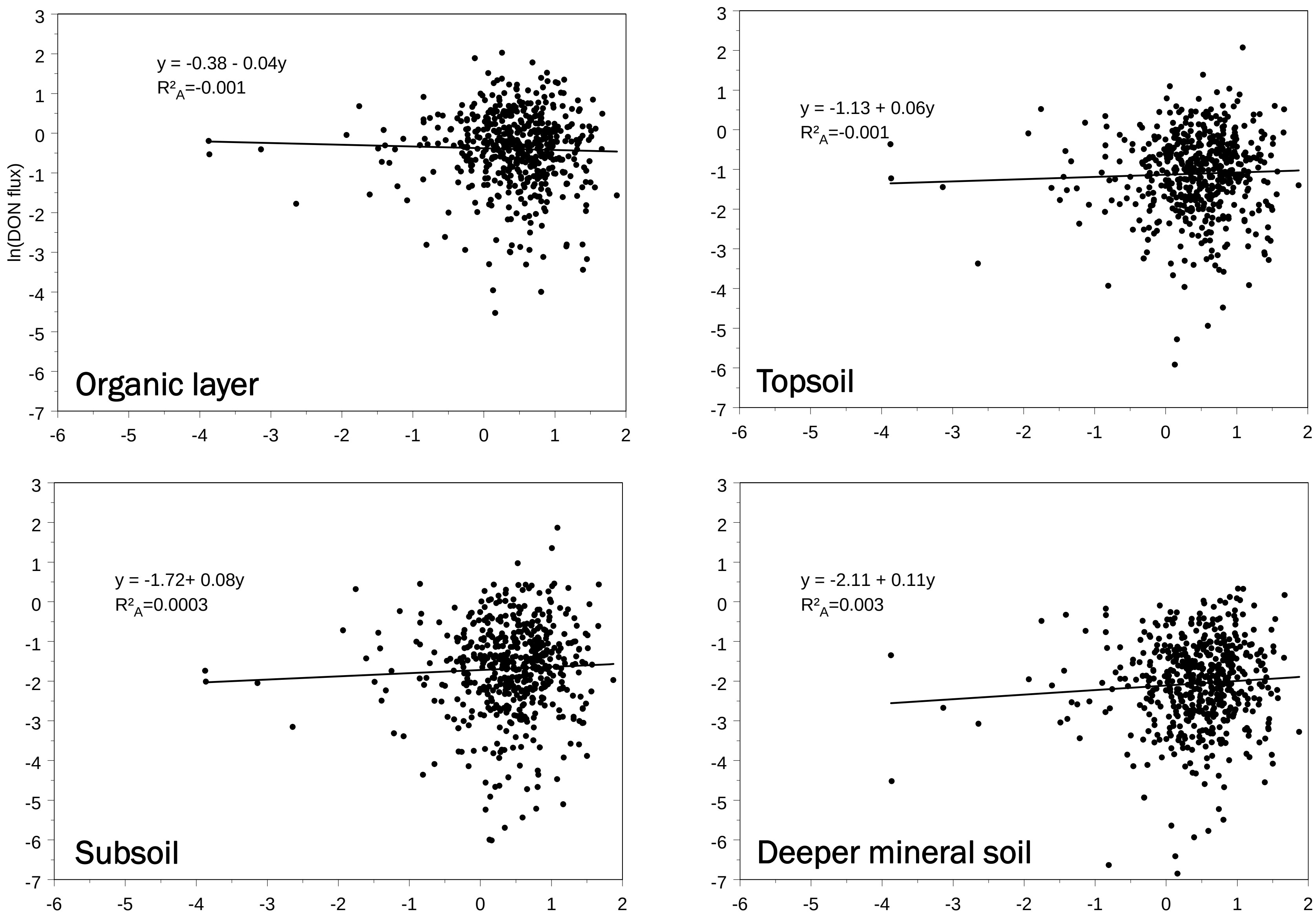
Plot	Mean	Slope
RAV	8.6	
BRA	7.3	
WIJ	5.9	
GON	6.5	0.03**
HOE	6.1	0.04***

Trend (SMK)

Plot	Mean	Slope
RAV	3.8	
BRA	2.7	
WIJ	1.2	
GON	2.5	
HOE	2.5	0.02***

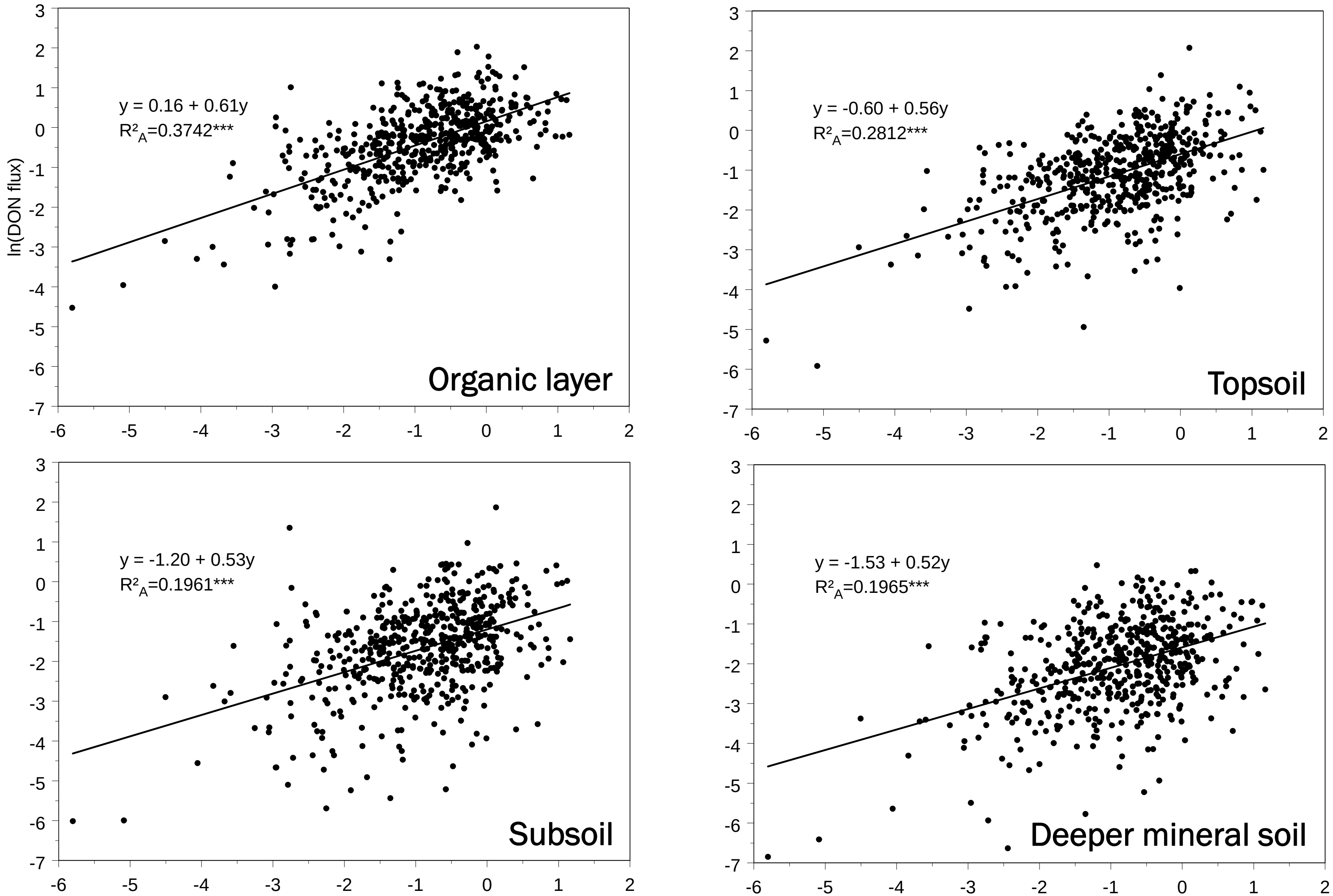
(↗). Longer times series needed (Waldner et al., in press)

Relation between (monthly) DON leaching and DIN deposition (2005-2013)



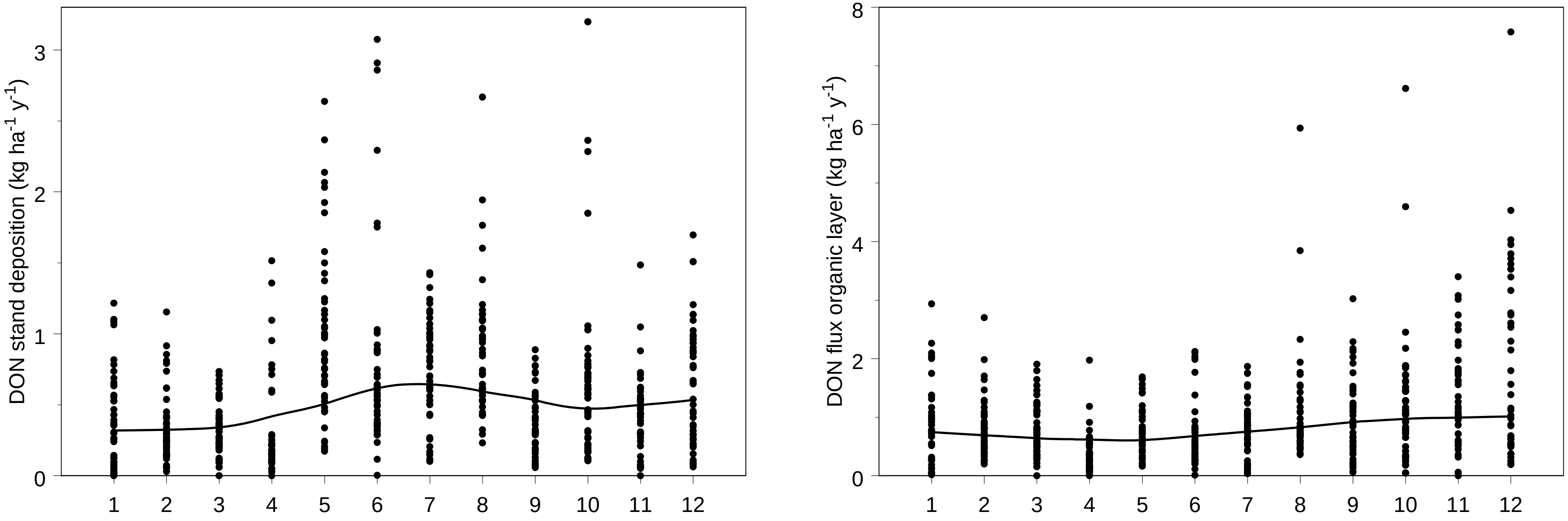
DON export not related to DIN input (➔ assumption for use of DIN:DON not violated)

Relation between (monthly) DON leaching and DON deposition (2005-2013)



On the contrast, DON export is significantly related to DON input at all depths

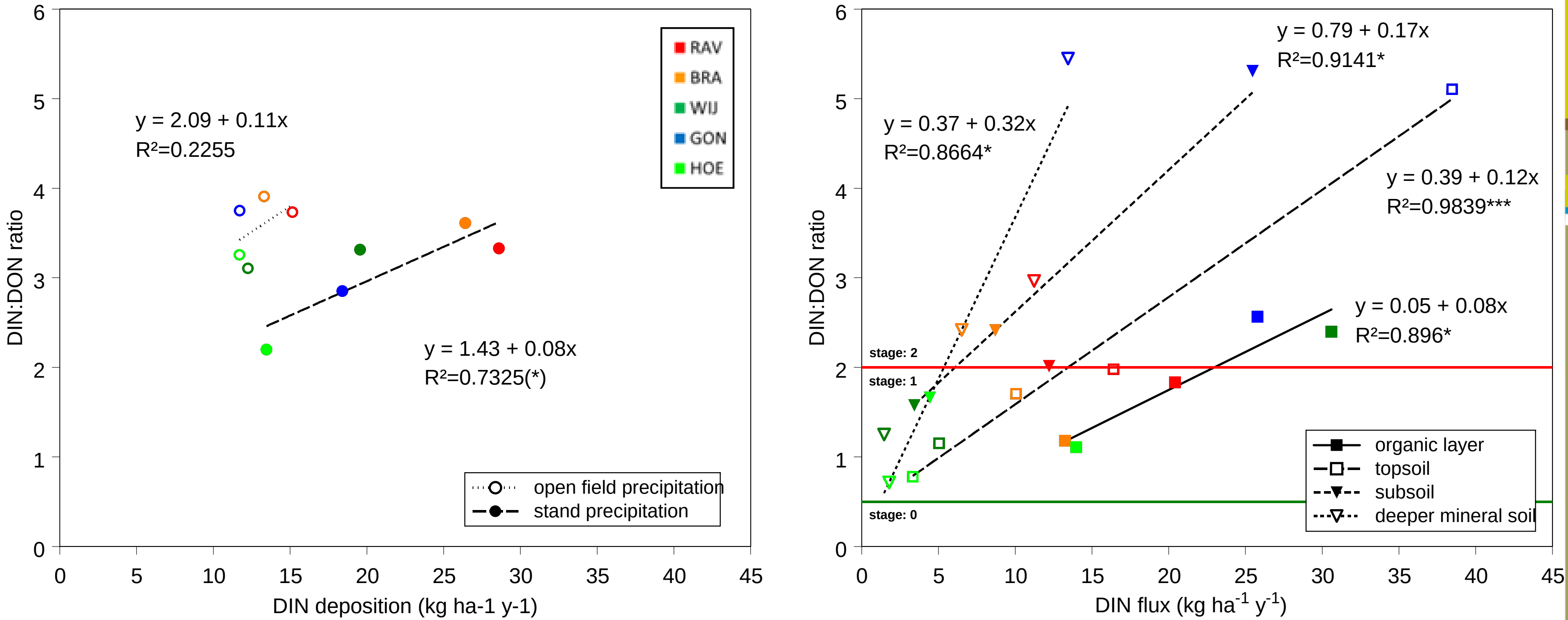
Relation between DON leaching and DON deposition (2005-2013)



BUT: Seasonal peak of DON in stand deposition (summer) not simultaneous with organic layer (winter) ➔ impact of DON deposition on soil solution DON is limited.

Similar result as for DOC (Verstraeten et al., 2014)

N-status - Relation between DIN:DON and DIN (2005-2013)



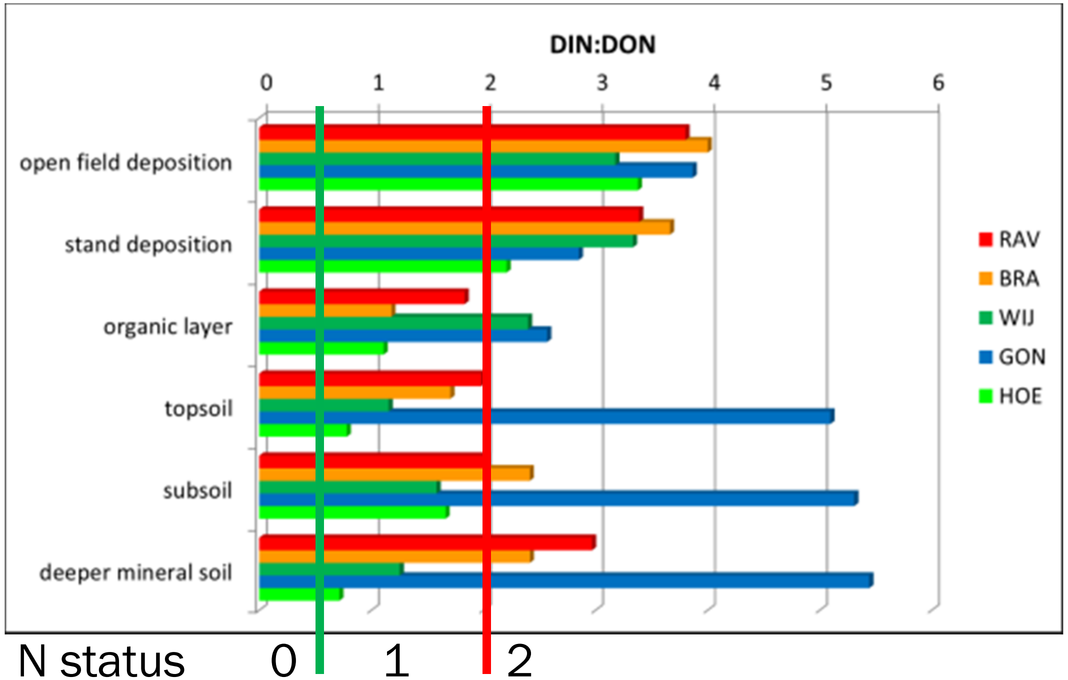
- **deposition**
  not significant (but only 5 plots)
  elevated DIN deposition (although DON is also elevated)

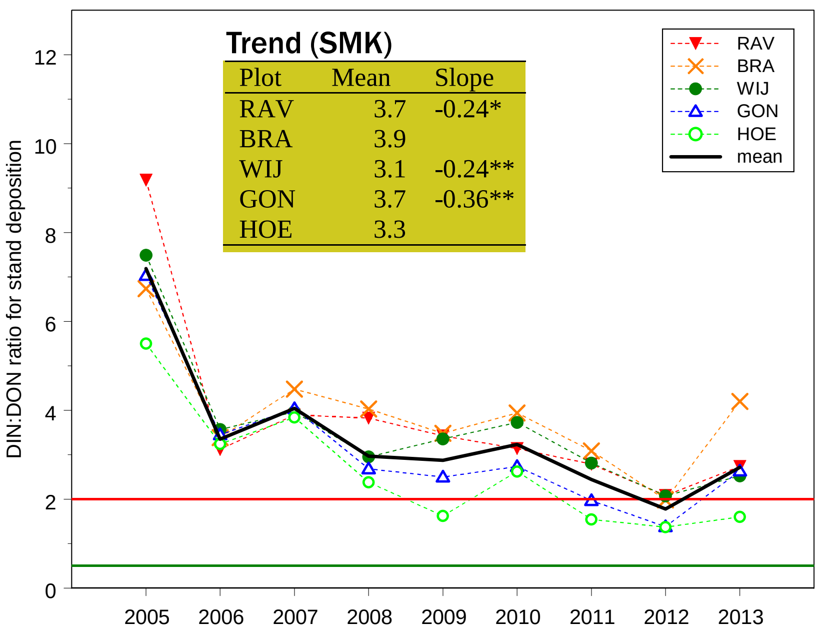
- **soil solution**
  significant at all depths (but only 5 plots)
  DIN:DON illustrates the differences in N saturation between plots
  Allows to evaluate the N status of each individual soil horizon

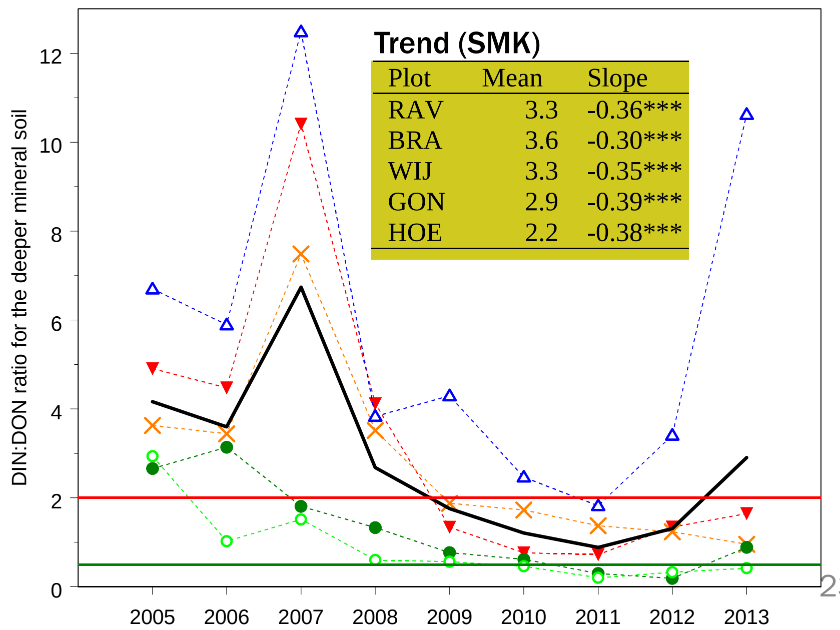
N status - DIN:DON (2005-2013)

- **deposition**
  average DIN:DON = 2.2-4.0
  ↘ DIN:DON (60% of plots)
- **soil solution**
  average DIN:DON = 0.7-5.4
  ↘ DIN:DON (100% of plots)
  GON highly N-saturated (2)
  RAV and BRA (2 → 1)
  HOE and WIJ (1 → 0)

2007 and 2013: dry summer followed by wet autumn → ‘flushing’
longer time series needed







Conclusions

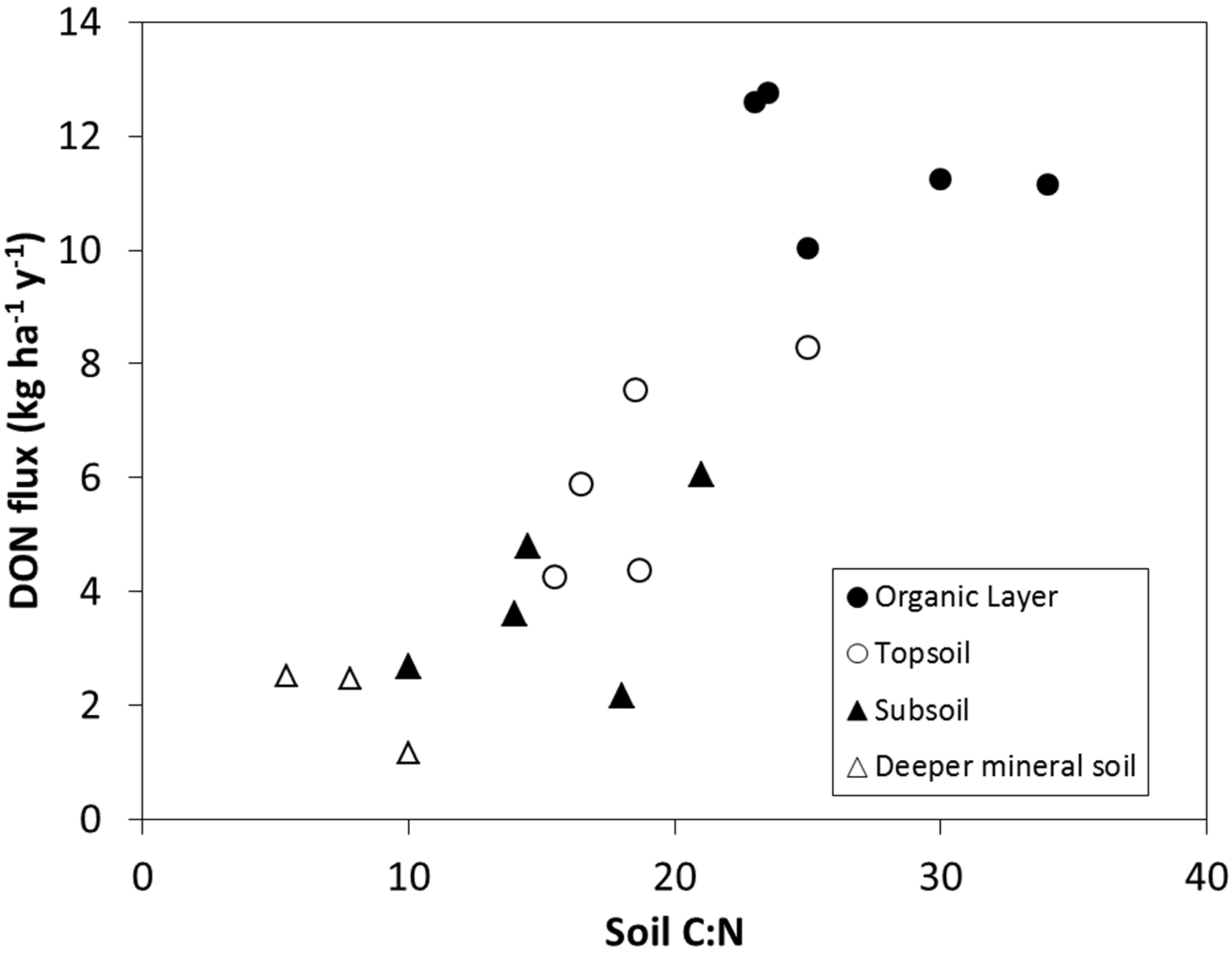
- In spite of high N depositions, N status of Flemish forests improved, but not at equal rate.

- The improving N status was indicated by:
  - ↗ pH of the deeper mineral soil — 100% of plots
  - ↘ NO_3^- leaching — 100% of plots
  - ↗ N retention — 80% of plots
  - ↘ months with exceedance of critical limits
  - ↘ DIN:DON ratio in soil solution — 100% of plots

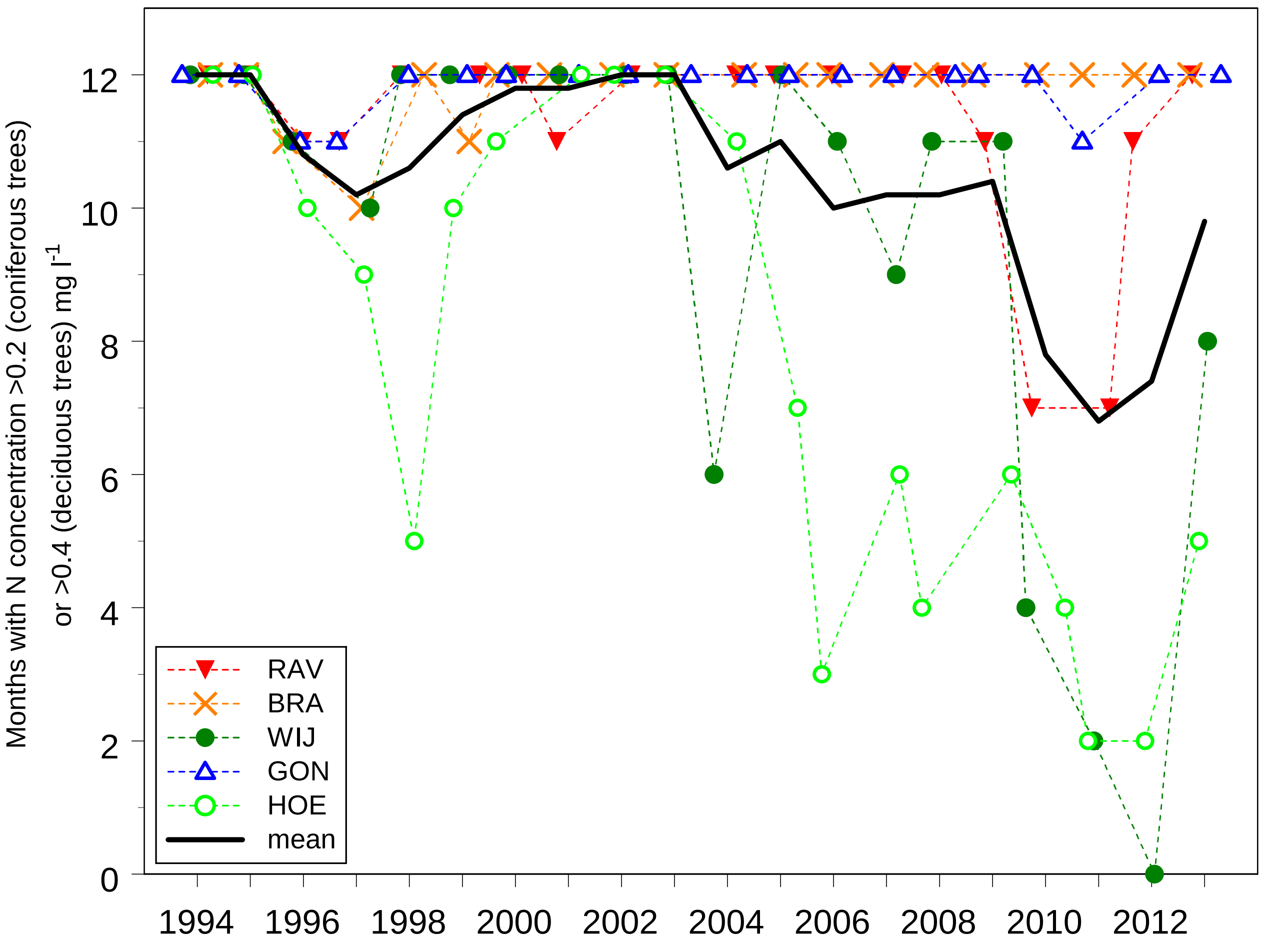
- 1 deciduous plot remained highly N saturated (N status = 2)
  2 coniferous plots are gradually recovering (N status = 2 → 1)
  2 deciduous plots showed fast recovery (N status = 1 → 0)


Questions?

Relationship between DON and Soil C:N (2005-2013)



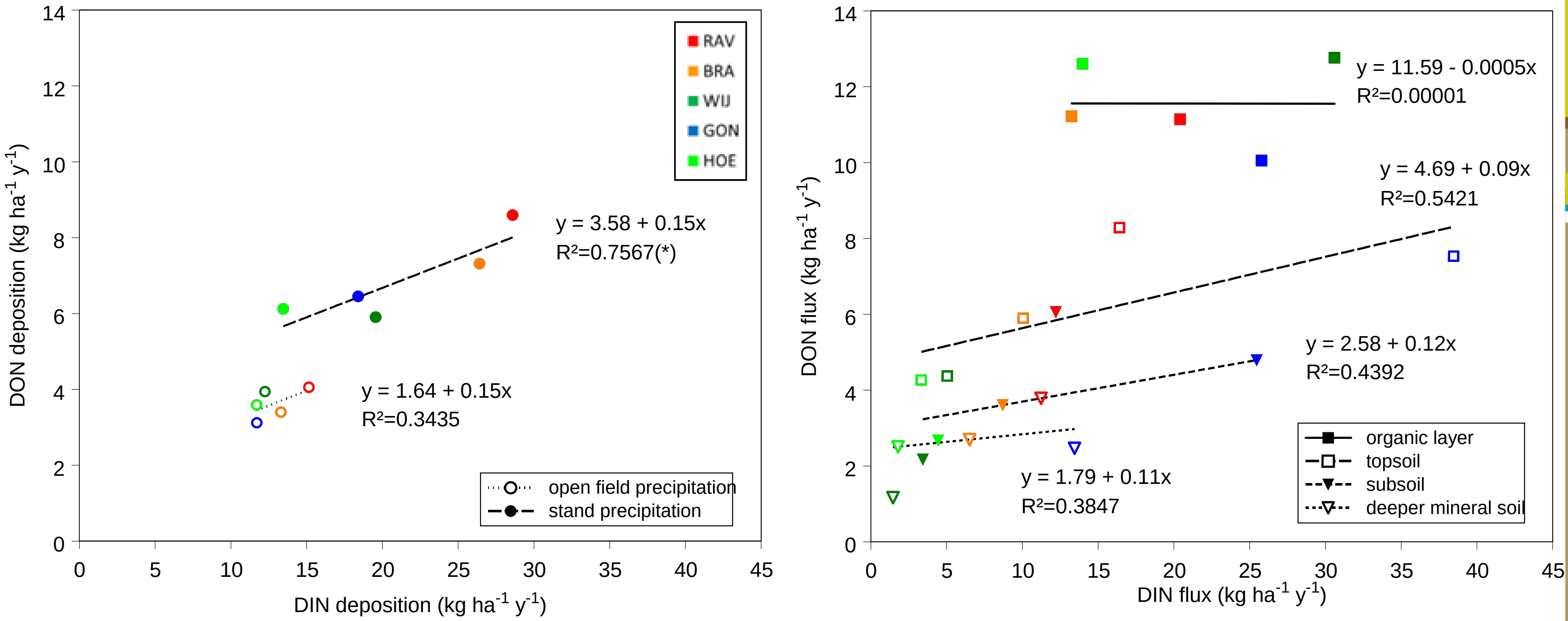
CL Nutrient deficiency for *Pinus* (>0.2 mg N l^{-1}) and *Quercus* and *Fagus* (>0.4 mg N l^{-1})



Trend (MK)

Plot	Mean	Slope
RAV	11.3	
BRA	11.8	
WIJ	9.6	-0.19**
GON	11.9	
HOE	7.8	-0.50**

Relation between DON and DIN (2005-2013)



Not significant