WHAT'S NEW IN THE FORSAFE-2 MODEL?

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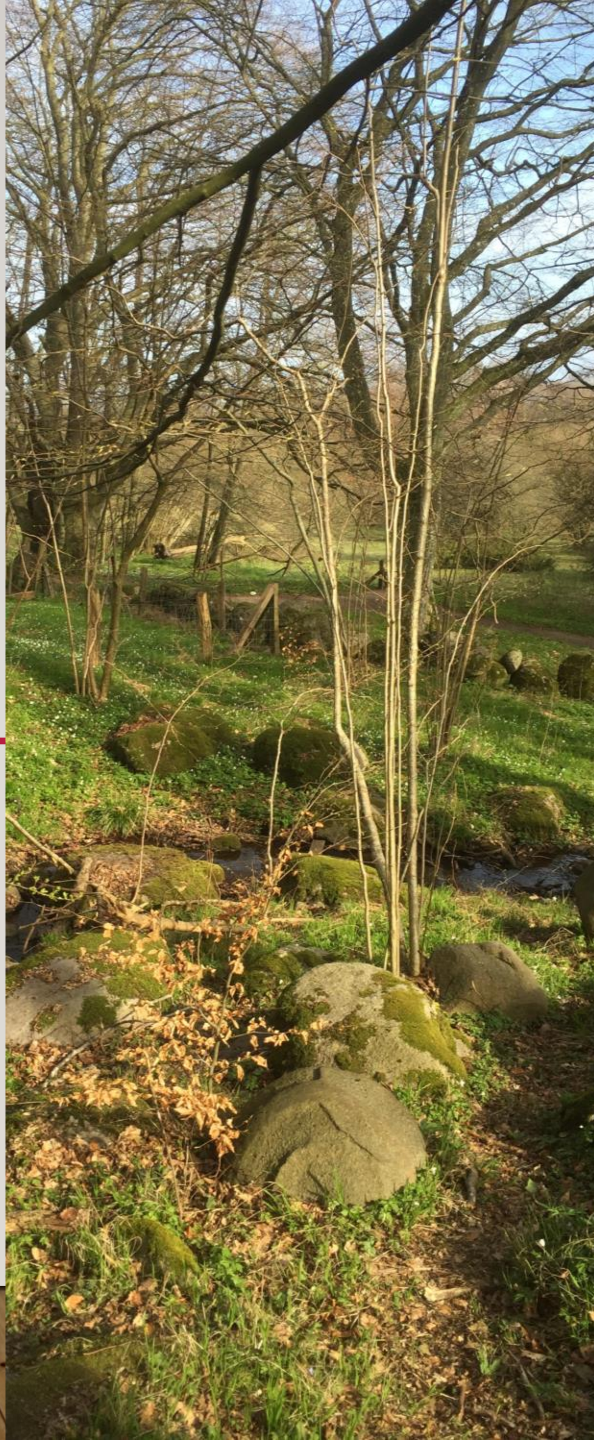


SUMMARY: PROFILE/FORSAFE 2.0 SYSTEM

- Extended the model to slopes and watersheds; streams
- Revised and updated weathering model; deeper soils
- Integrated C-N-P dynamic cycles inside model
- It works for critical loads based on biodiversity
- Biodiversity based critical loads have been mapped for Sweden

MINERAL DISSOLUTION RATES,

INCLUDING H^+, H_20, CO_2, ORGANIC ACID (R), OH^- AND RETARDING FUNCTIONS BASED ON BC, Al^{3+}, R^-, Si

$$
\begin{aligned}
\text{Rate} = \; & 10^{(pK_H+E_H\left(\frac{1}{T}+\frac{1}{T_{ref}}\right)} \cdot \{H^+\}^{n1} \cdot \frac{1}{\left(1+\frac{BC}{BC_{lim}}\right)^{m1}\cdot\left(1+\frac{\{Al3+\}}{Al^{3+}_{lim}}\right)^{p1}\cdot\left(1+K_{Si}\left(\frac{\{Si\}}{Si_{lim}}\right)^{q1}\right)} \\
& + 10^{(pK_{H2O}+E_{H2O}\left(\frac{1}{T}+\frac{1}{T_{ref}}\right)} \cdot \frac{1}{\left(1+\frac{BC}{BC_{lim}}\right)^{m2}\cdot\left(1+\frac{\{Al3+\}}{Al^{3+}_{lim}}\right)^{p2}\cdot\left(1+K_{Si}\left(\frac{\{Si\}}{Si_{lim}}\right)^{q2}\right)} \\
& + 10^{(pK_{CO2}+E_{CO2}\left(\frac{1}{T}+\frac{1}{T_{ref}}\right)} \cdot \frac{P^{n3}_{CO2}}{1+K_{CO2}\cdot P^{n3}_{CO2}} \cdot \frac{1}{\left(1+\frac{BC}{BC_{lim}}\right)^{m3}\cdot\left(1+\frac{\{Al3+\}}{Al^{3+}_{lim}}\right)^{p3}\cdot\left(1+K_{Si}\left(\frac{\{Si\}}{Si_{lim}}\right)^{q3}\right)} \\
& + 10^{(pK_R+E_R\left(\frac{1}{T}+\frac{1}{T_{ref}}\right)} \cdot \frac{\{R^-\}^{n4}}{\left(1+\frac{\{R^-\}}{R^-_{lim}}\right)^{n4}\cdot} \cdot \frac{1}{\left(1+\frac{BC}{BC_{lim}}\right)^{m4}\cdot\left(1+\frac{\{Al3+\}}{Al^{3+}_{lim}}\right)^{p4}\cdot\left(1+K_{Si}\left(\frac{\{Si\}}{Si_{lim}}\right)^{q4}\right)} \\
& + 10^{(pK_{OH}+E_{OH}\left(\frac{1}{T}+\frac{1}{T_{ref}}\right)} \cdot \{OH^-\}^{n1} \frac{1}{\left(1+\frac{BC}{BC_{lim}}\right)^{m5}\cdot\left(1+\frac{\{Al3+\}}{Al^{3+}_{lim}}\right)^{p5}\cdot\left(1+K_{Si}\left(\frac{\{Si\}}{Si_{lim}}\right)^{q5}\right)}
\end{aligned}
$$

REVISING AND EXPANDING KINETIC COEFFICIENTS AND BRAKES, USING EXPERIMENTAL DATA

11 mineral families:

- Feldspars
- Neosilicates
- Pyroxenes
- Amphiboles
- Phyllosilicates
- Limestones
- Cyclosilicates
- Sorosilicates
- Phosphates
- Clays
- Volcanic glasses

(93 different minerals)

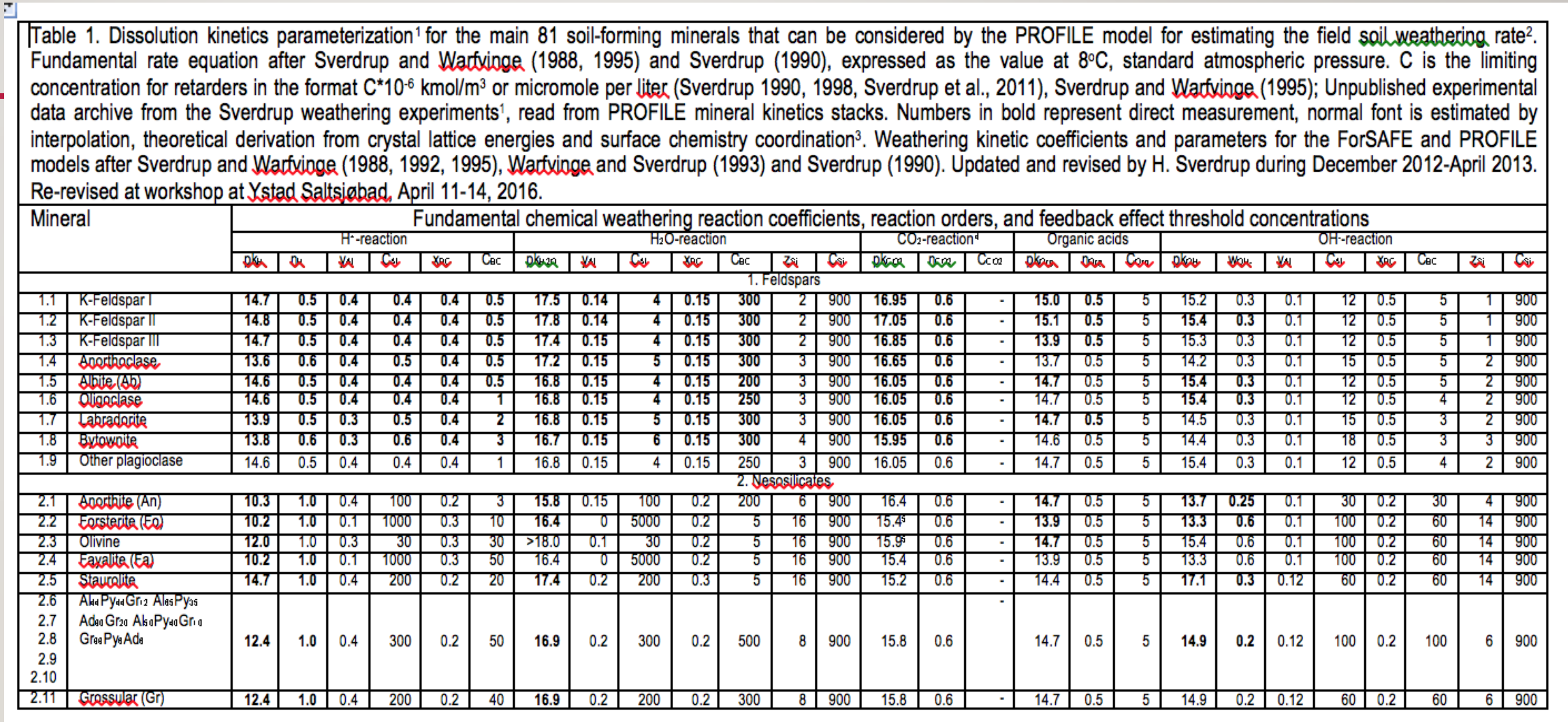
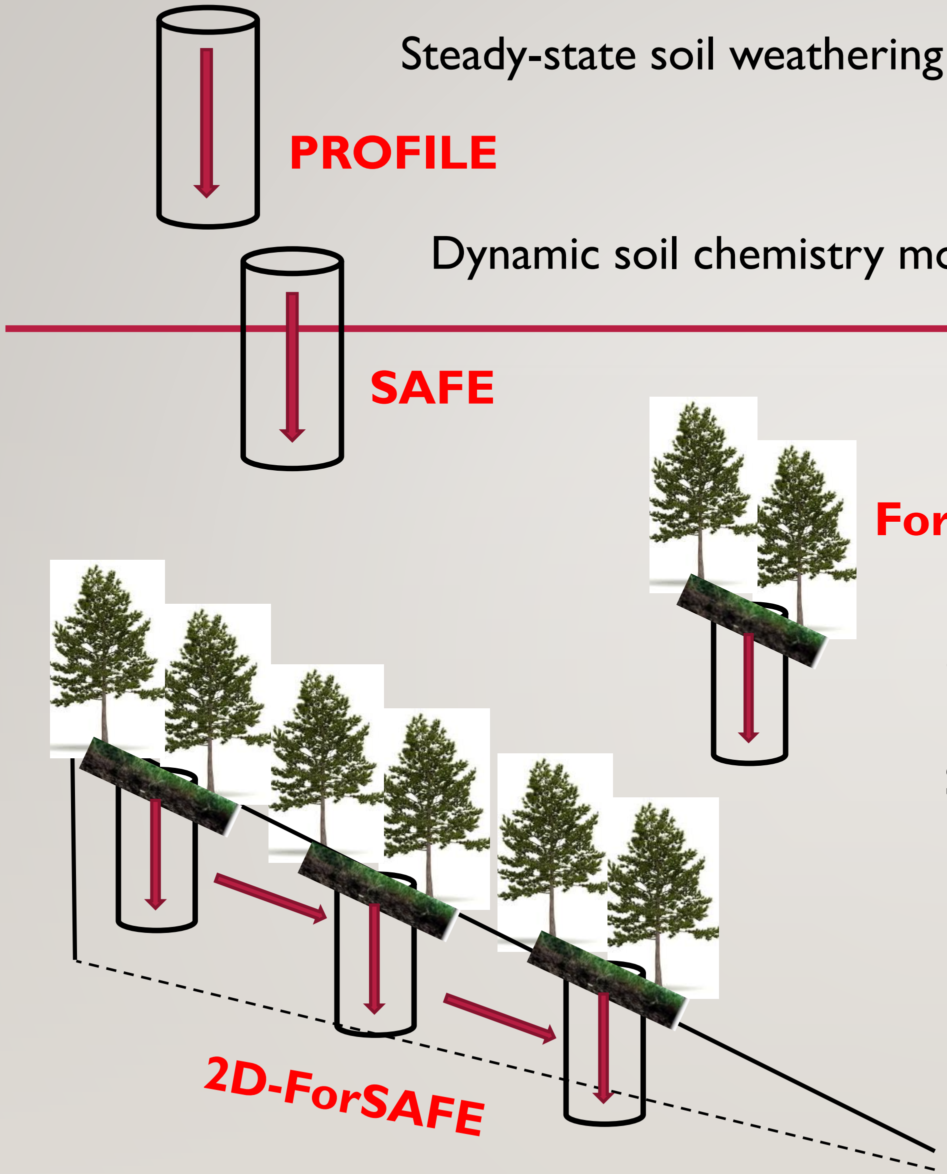


Table 1. Dissolution kinetics parameterization[1] for the main 81 soil-forming minerals that can be considered by the PROFILE model for estimating the field soil weathering rate[2]. Fundamental rate equation after Sverdrup and Warfvinge (1988, 1995) and Sverdrup (1990), expressed as the value at 8°C, standard atmospheric pressure. C is the limiting concentration for retarders in the format C*10^{-6} kmol/m^3 or micromole per liter (Sverdrup 1990, 1998, Sverdrup et al., 2011), Sverdrup and Warfvinge (1995); Unpublished experimental data archive from the Sverdrup weathering experiments[1], read from PROFILE mineral kinetics stacks. Numbers in bold represent direct measurement, normal font is estimated by interpolation, theoretical derivation from crystal lattice energies and surface chemistry coordination[3]. Weathering kinetic coefficients and parameters for the ForSAFE and PROFILE models after Sverdrup and Warfvinge (1988, 1992, 1995), Warfvinge and Sverdrup (1993) and Sverdrup (1990). Updated and revised by H. Sverdrup during December 2012-April 2013. Re-revised at workshop at Ystad Saltsjøbad, April 11-14, 2016.

Mineral		Fundamental chemical weathering reaction coefficients, reaction orders, and feedback effect threshold concentrations																										
		H^+-reaction						H_2O-reaction							CO_2-reaction[4]			Organic acids			OH^--reaction							
		pK_H	n_H	y_{Al}	C_{Al}	x_{BC}	C_{BC}	pK_{H2O}	y_{Al}	C_{Al}	x_{BC}	C_{BC}	z_{Si}	C_{Si}	pK_{CO2}	n_{CO2}	C_{CO2}	pK_{Org}	n_{Org}	C_{Org}	pK_{OH}	w_{OH}	y_{Al}	C_{Al}	x_{BC}	C_{BC}	z_{Si}	C_{Si}
	1. Feldspars																											
1.1	K-Feldspar I	**14.7**	**0.5**	**0.4**	**0.4**	**0.4**	**0.5**	**17.5**	**0.14**	**4**	**0.15**	**300**	2	900	**16.95**	**0.6**	-	**15.0**	**0.5**	5	15.2	0.3	0.1	12	0.5	5	1	900
1.2	K-Feldspar II	**14.8**	**0.5**	**0.4**	**0.4**	**0.4**	**0.5**	**17.8**	**0.14**	**4**	**0.15**	**300**	2	900	**17.05**	**0.6**	-	**15.1**	**0.5**	5	**15.4**	**0.3**	0.1	12	0.5	5	1	900
1.3	K-Feldspar III	**14.7**	**0.5**	**0.4**	**0.4**	**0.4**	**0.5**	**17.4**	**0.15**	**4**	**0.15**	**300**	2	900	**16.85**	**0.6**	-	**13.9**	**0.5**	5	15.3	0.3	0.1	12	0.5	5	1	900
1.4	Anorthoclase	**13.6**	**0.6**	**0.4**	**0.5**	**0.4**	**0.5**	**17.2**	**0.15**	**5**	**0.15**	**300**	3	900	**16.65**	**0.6**	-	13.7	0.5	5	14.2	0.3	0.1	15	0.5	5	2	900
1.5	Albite (Ab)	**14.6**	**0.5**	**0.4**	**0.4**	**0.4**	**0.5**	**16.8**	**0.15**	**4**	**0.15**	**200**	3	900	**16.05**	**0.6**	-	**14.7**	0.5	5	**15.4**	**0.3**	0.1	12	0.5	5	2	900
1.6	Oligoclase	**14.6**	**0.5**	**0.4**	**0.4**	**0.4**	**1**	**16.8**	**0.15**	**4**	**0.15**	**250**	3	900	**16.05**	**0.6**	-	14.7	0.5	5	**15.4**	**0.3**	0.1	12	0.5	4	2	900
1.7	Labradorite	**13.9**	**0.5**	**0.3**	**0.5**	**0.4**	**2**	**16.8**	**0.15**	**5**	**0.15**	**300**	3	900	**16.05**	**0.6**	-	**14.7**	**0.5**	5	14.5	0.3	0.1	15	0.5	3	2	900
1.8	Bytownite	**13.8**	**0.6**	**0.3**	**0.6**	**0.4**	**3**	**16.7**	**0.15**	**6**	**0.15**	**300**	4	900	**15.95**	**0.6**	-	14.6	0.5	5	14.4	0.3	0.1	18	0.5	3	3	900
1.9	Other plagioclase	14.6	0.5	0.4	0.4	0.4	1	16.8	0.15	4	0.15	250	3	900	16.05	0.6	-	14.7	0.5	5	15.4	0.3	0.1	12	0.5	4	2	900
	2. Nesosilicates																											
2.1	Anorthite (An)	**10.3**	**1.0**	0.4	100	0.2	3	**15.8**	0.15	100	0.2	200	6	900	16.4	0.6	-	**14.7**	0.5	5	**13.7**	**0.25**	0.1	30	0.2	30	4	900
2.2	Forsterite (Fo)	**10.2**	**1.0**	0.1	1000	0.3	10	**16.4**	0	5000	0.2	5	16	900	15.4[5]	0.6	-	**13.9**	0.5	5	**13.3**	**0.6**	0.1	100	0.2	60	14	900
2.3	Olivine	**12.0**	1.0	0.3	30	0.3	30	>18.0	0.1	30	0.2	5	16	900	15.9[5]	0.6	-	**14.7**	0.5	5	15.4	0.6	0.1	100	0.2	60	14	900
2.4	Fayalite (Fa)	**10.2**	**1.0**	0.1	1000	0.3	50	16.4	0	5000	0.2	5	16	900	15.4	0.6	-	13.9	0.5	5	13.3	0.6	0.1	100	0.2	60	14	900
2.5	Staurolite	**14.7**	**1.0**	0.4	200	0.2	20	**17.4**	0.2	200	0.3	5	16	900	15.2	0.6	-	14.4	0.5	5	**17.1**	**0.3**	0.12	60	0.2	60	14	900
2.6 2.7 2.8 2.9 2.10	$Al_{44}Py_{44}Gr_{12}$ $Al_{65}Py_{35}$ $Ad_{80}Gr_{20}$ $Al_{50}Py_{40}Gr_{10}$ $Gr_{88}Py_{8}Ad_{8}$	**12.4**	**1.0**	0.4	300	0.2	50	**16.9**	0.2	300	0.2	500	8	900	15.8	0.6	-	14.7	0.5	5	**14.9**	**0.2**	0.12	100	0.2	100	6	900
2.11	Grossular (Gr)	**12.4**	**1.0**	0.4	200	0.2	40	**16.9**	0.2	200	0.2	300	8	900	15.8	0.6	-	14.7	0.5	5	14.9	0.2	0.12	60	0.2	60	6	900

PROFILE, SAFE, ForSAFE



1988

PROFILE

Steady-state soil weathering model (Sverdrup & Warfvinge)

1993

SAFE

Dynamic soil chemistry model (Warfvinge et al.)

2005

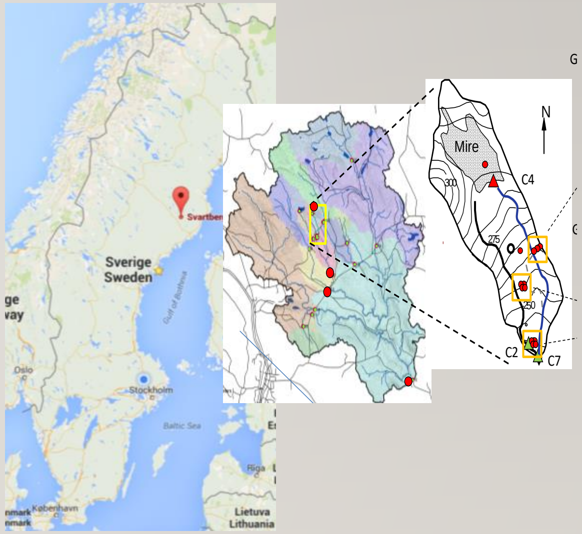
ForSAFE

Coupled forest ecosystem model (Wallman et al., Sverdrup et al.)

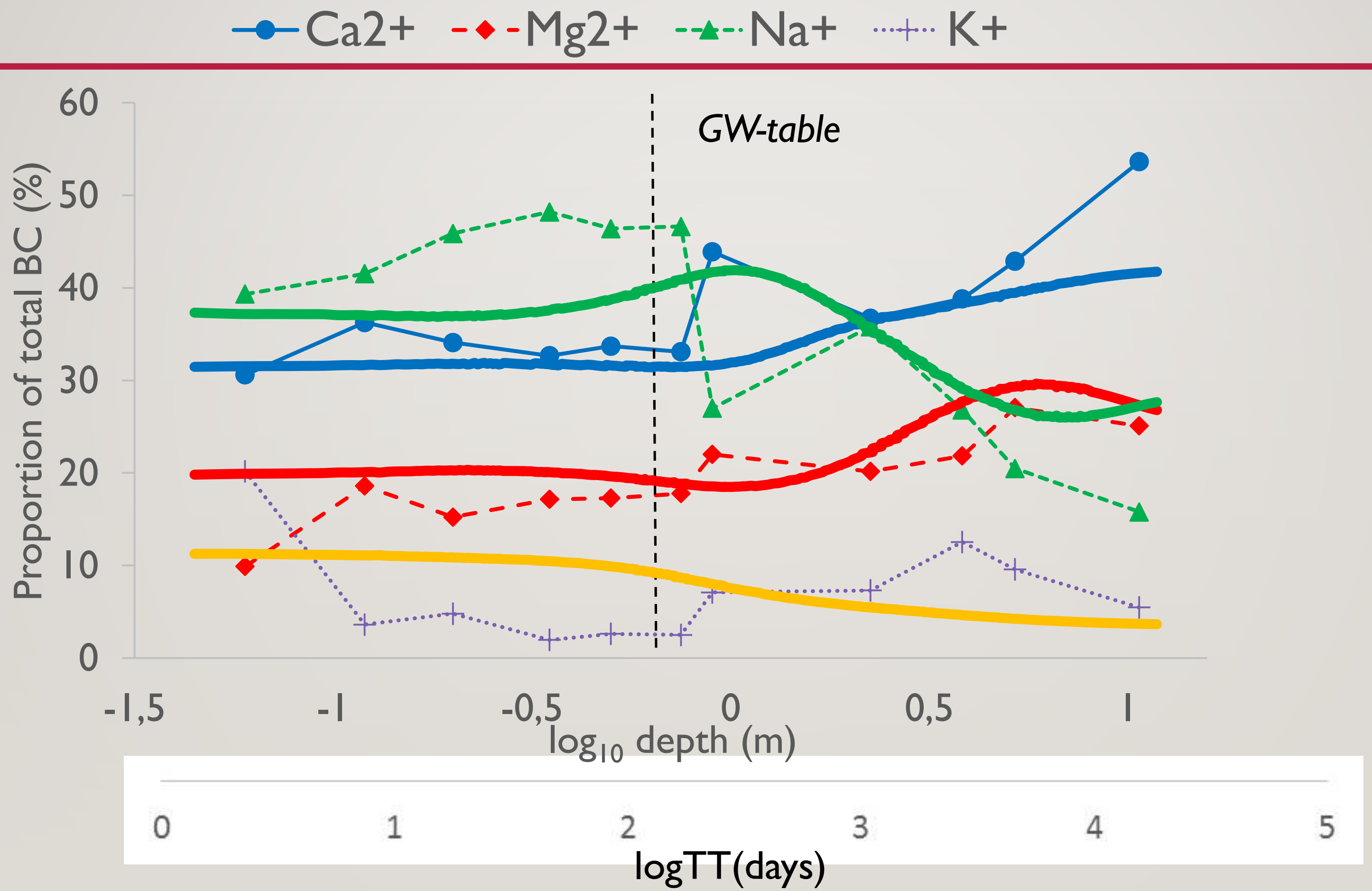
2016

2D-ForSAFE

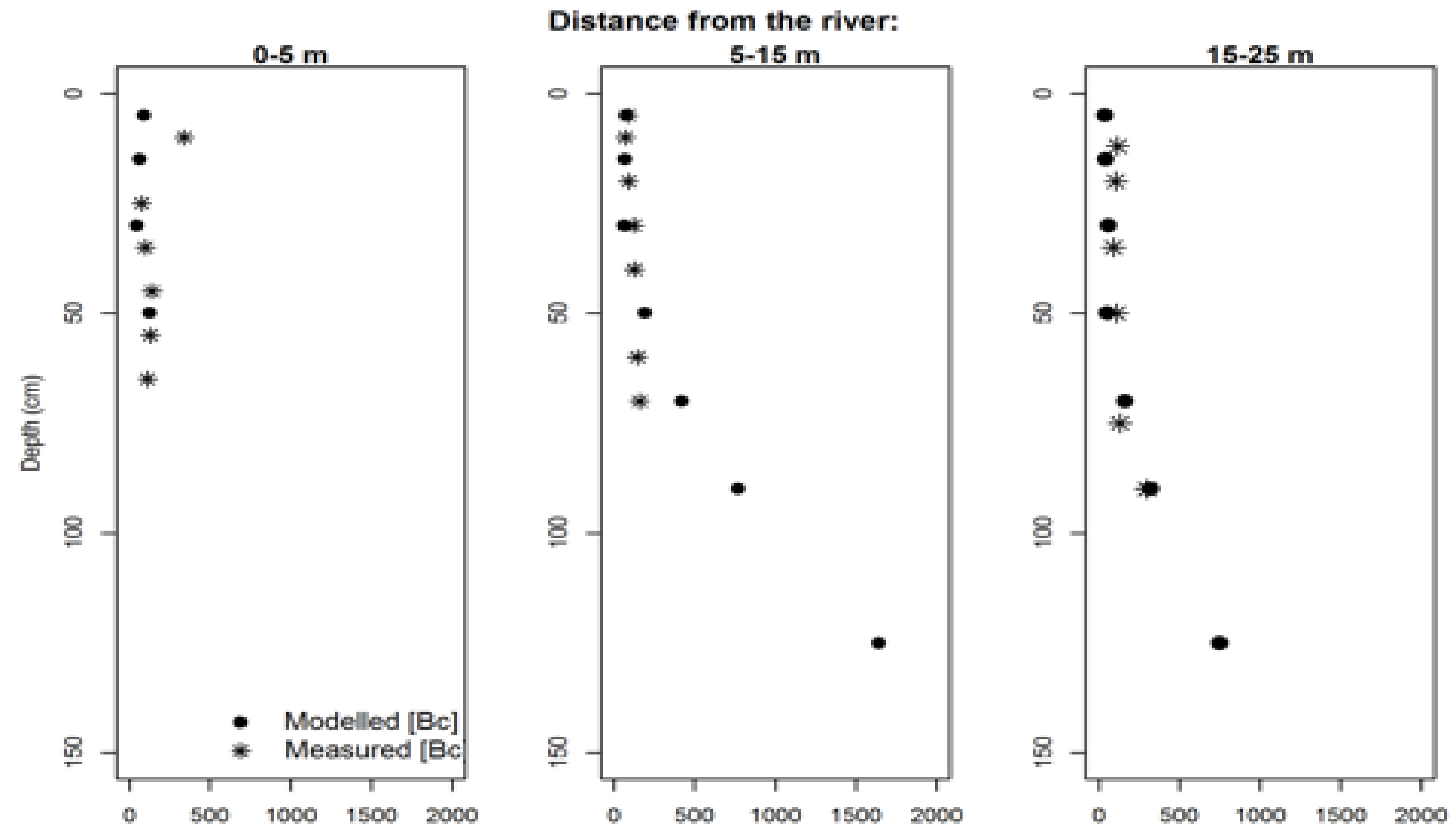
2D forest ecosystem model (Zanchi et al., Erlandson et al.)



DEPTH PROFILE VS. MODEL (NEW PROFILE EQUATIONS)



GETTING SOIL CHMISTRY TO THE STREAM



PHOSPHORUS CYCLE INSIDE THE FORSAFE MODEL

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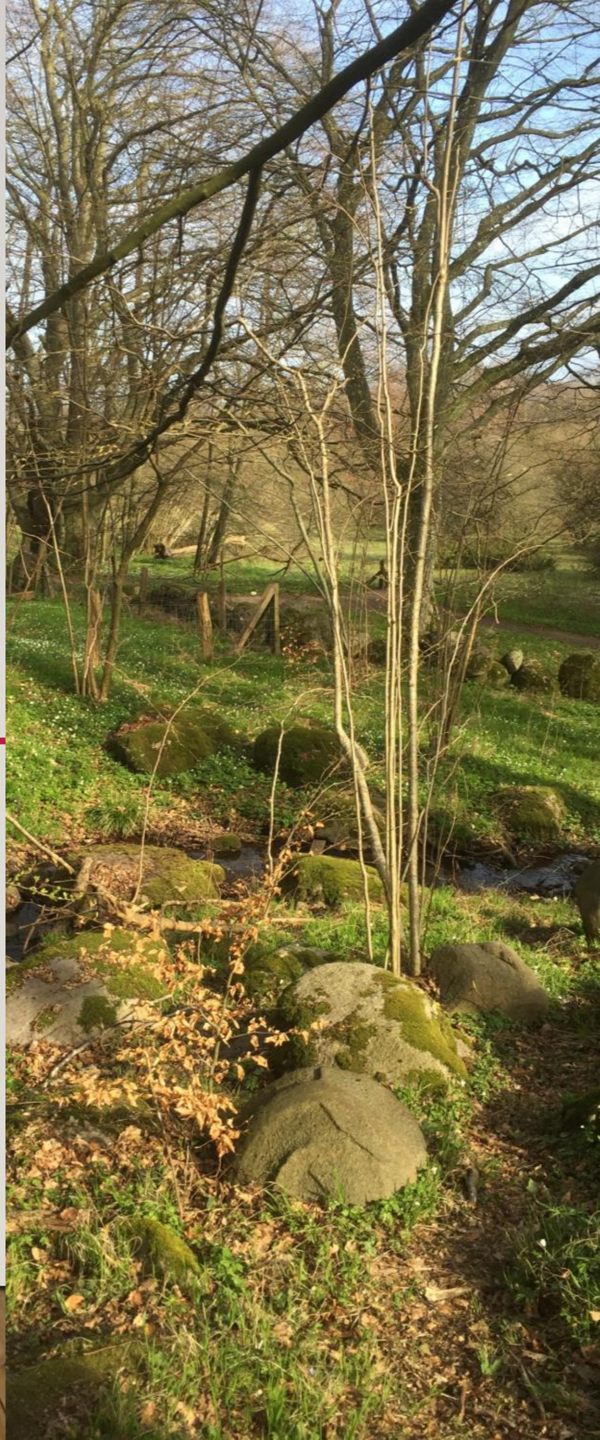
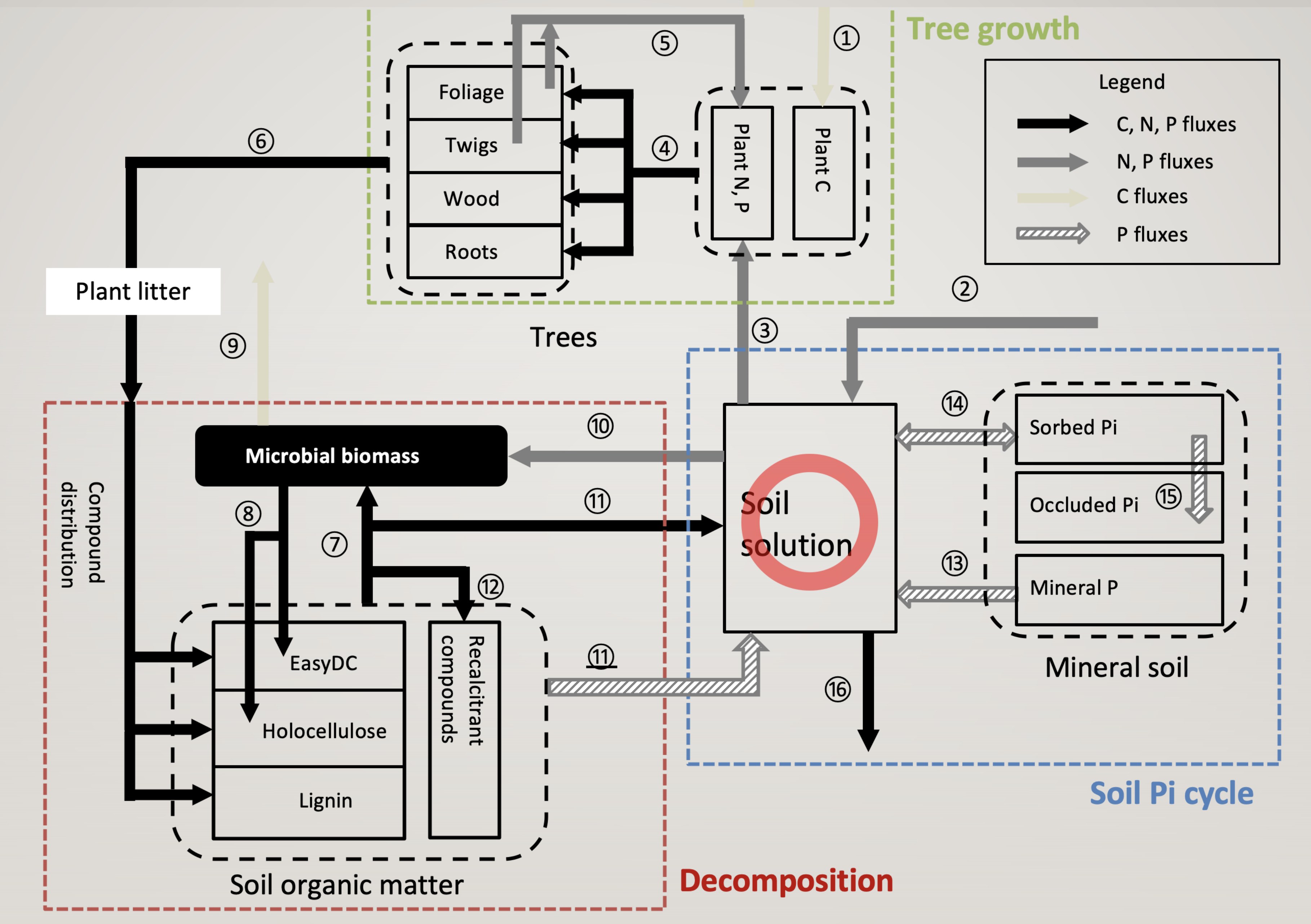
CEC, LUND UNIVERSITY, STOCKHOLM UNIVERSITY, HAMAR UNIVERSITY



Phosphurus cycle in ForSAFE



Tree growth

Legend

C, N, P fluxes

N, P fluxes

C fluxes

P fluxes

Foliage

Twigs

Wood

Roots

Plant N, P

Plant C

Trees

Plant litter

①
②
③
④
⑤
⑥
⑨

Microbial biomass

Compound distribution

⑦
⑧
⑩
⑪
⑫

EasyDC

Holocellulose

Lignin

Recalcitrant compounds

Soil organic matter

Decomposition

⑪

Soil solution

⑬
⑭
⑮
⑯

Sorbed Pi

Occluded Pi

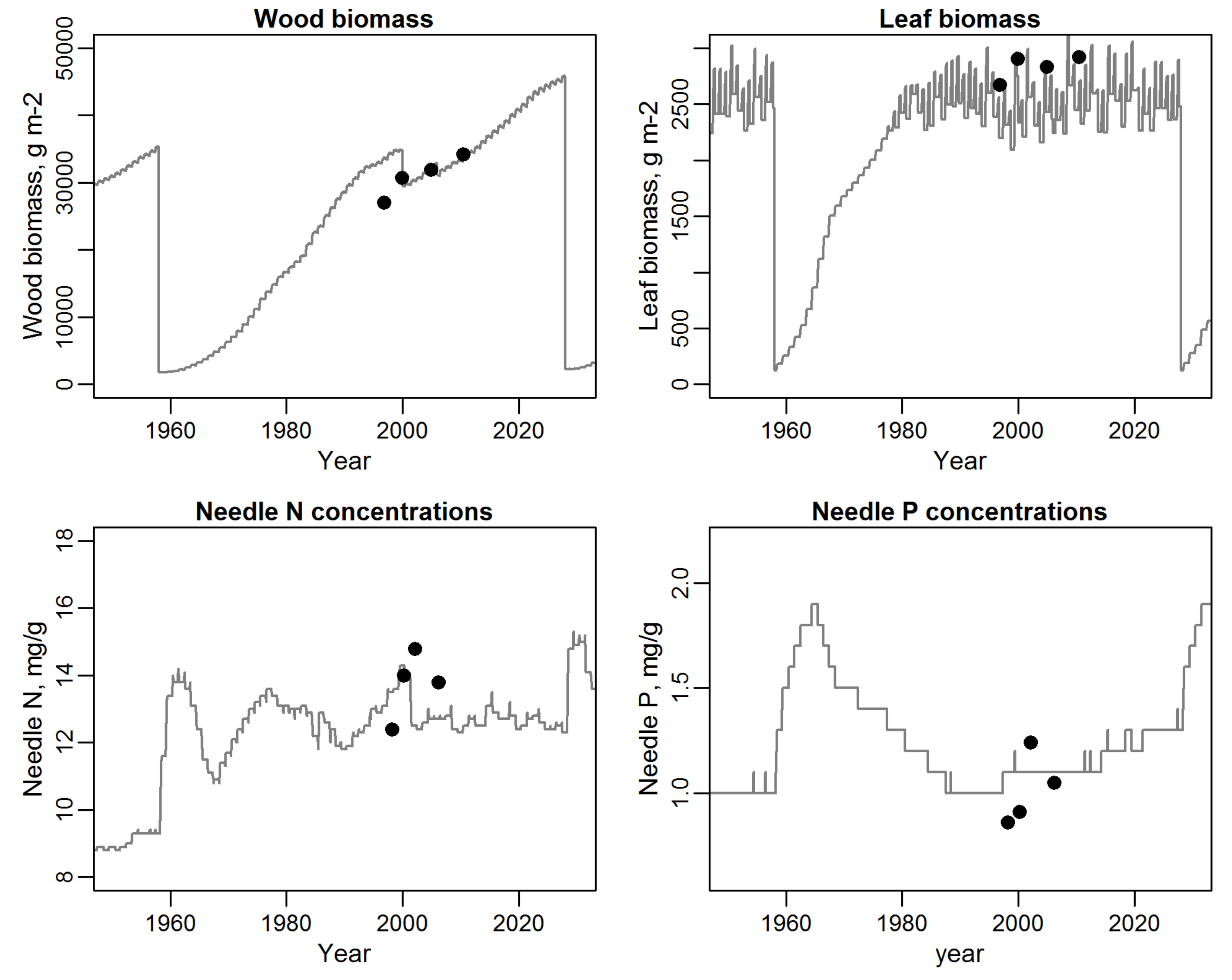
Mineral P

Mineral soil

Soil Pi cycle

Figure 4. Major carbon (C), nitrogen (N) and phosphorus (P) processes included in the new ForSAFE.
① photosynthesis, ② deposition (fertilization), ③ plant nutrient uptake, ④ C and nutrient allocation,⑤ retranslocation, ⑥ litter fall, ⑦ microbial assimilation, ⑧ microbial decay and overflow metabolism, ⑨ microbial respiration, ⑩ immobilization, ⑪ biological mineralization and overflow metabolism mineralization, ⑪ biochemical mineralization, ⑫ humification, ⑬ P weathering, ⑭ P sorption/desorption, ⑮ P occlusion, ⑯ nutrient leaching (percolation and surface flow). EDC denotes easy decomposable carbon.

N & P nutrition in a southwestern Swedish forest



SOIL MICROBIOLOGY AND IMPROVED NITROGEN DYNAMICS INCLUDED IN THE FORSAFE MODEL

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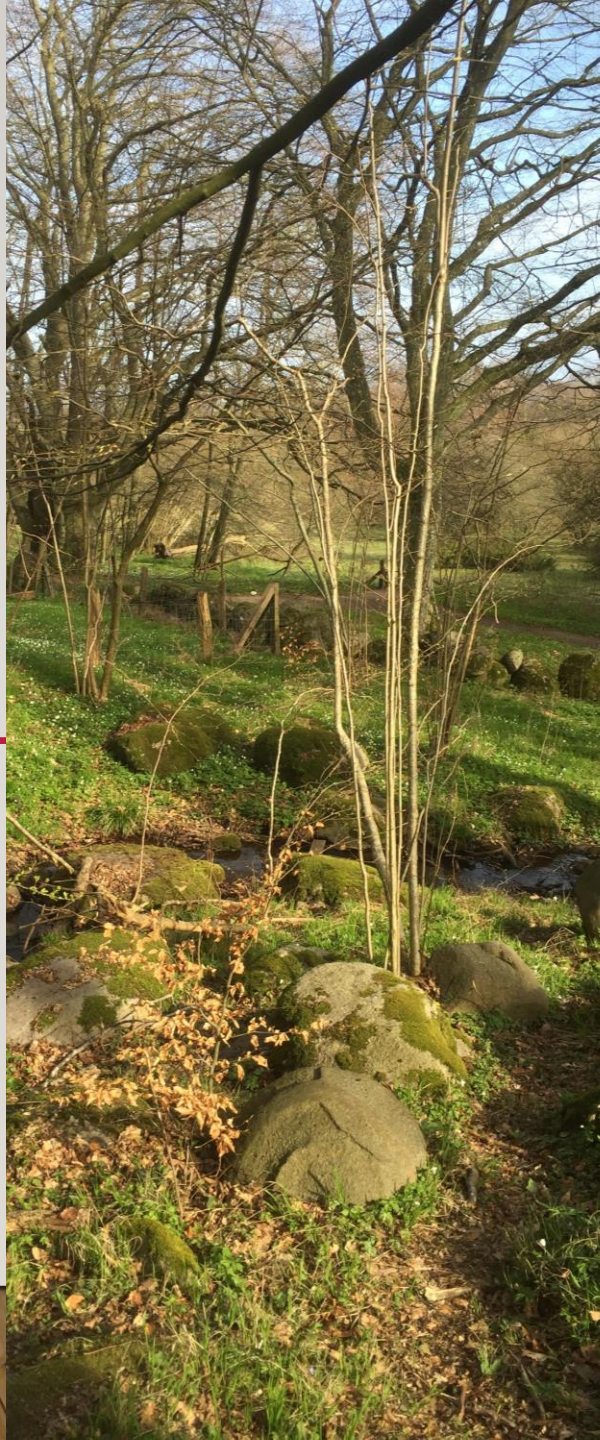


ForSAFE-2.0;

N leaching following a clearcut is mostly determined by the net balance between mineralization on one hand (output), and uptake (Nutrient removal by both microbial and by plants growth) on the other, resulting in new litterfall (input).
(Zanchi et al., 2014)

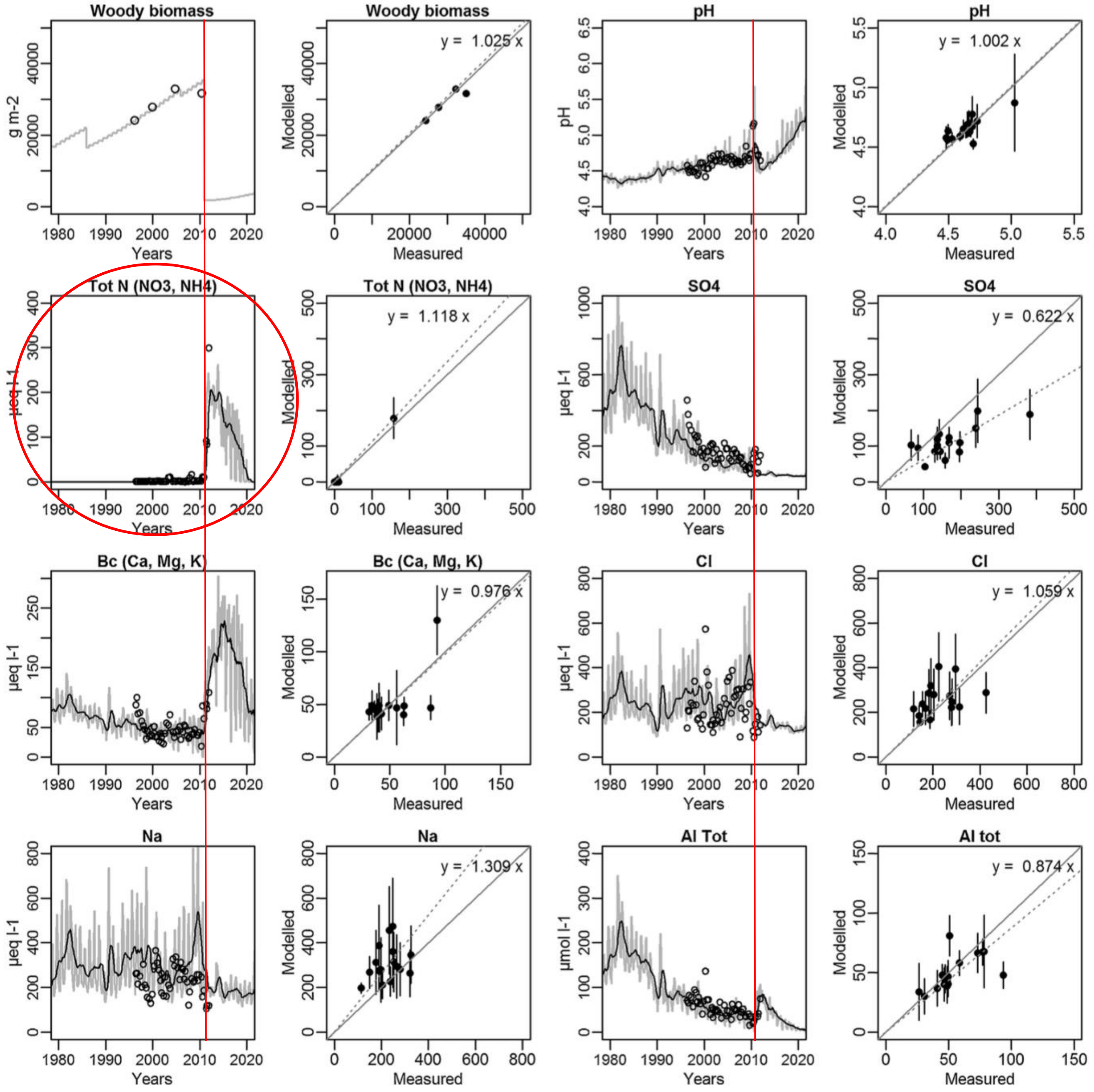


Fig. 3. Comparison of modelled data to measured data in Västra Torup. For each element there are two types of graphs. In the first type, monthly modelled results (grey line) and the moving average on a yearly basis (black line) are compared to measured data (points) over the years. In the second type of graph, the annual means of modelled and measured data in 1996–2011 are plotted against each other. The dotted line and its slope reported in the equation ($y = ax$) are an indication of the discrepancy between modelled and measured data.

ForSAFE 2.0

Following two consecutive storms, the peaks in N leaching is mostly explained by a loss of microbial ability to retain N due to the disturbance.
(Yu et al., 2016)

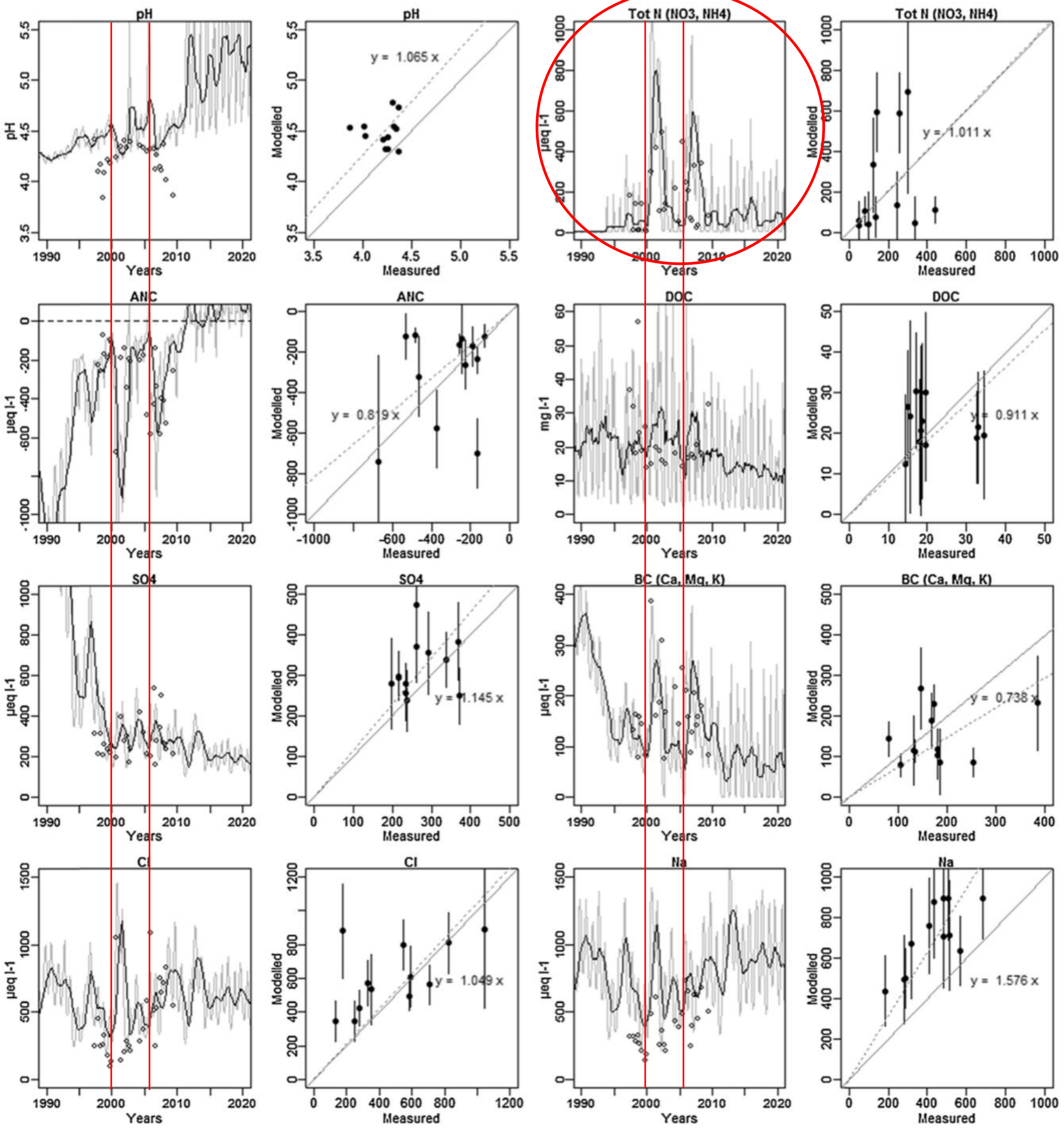
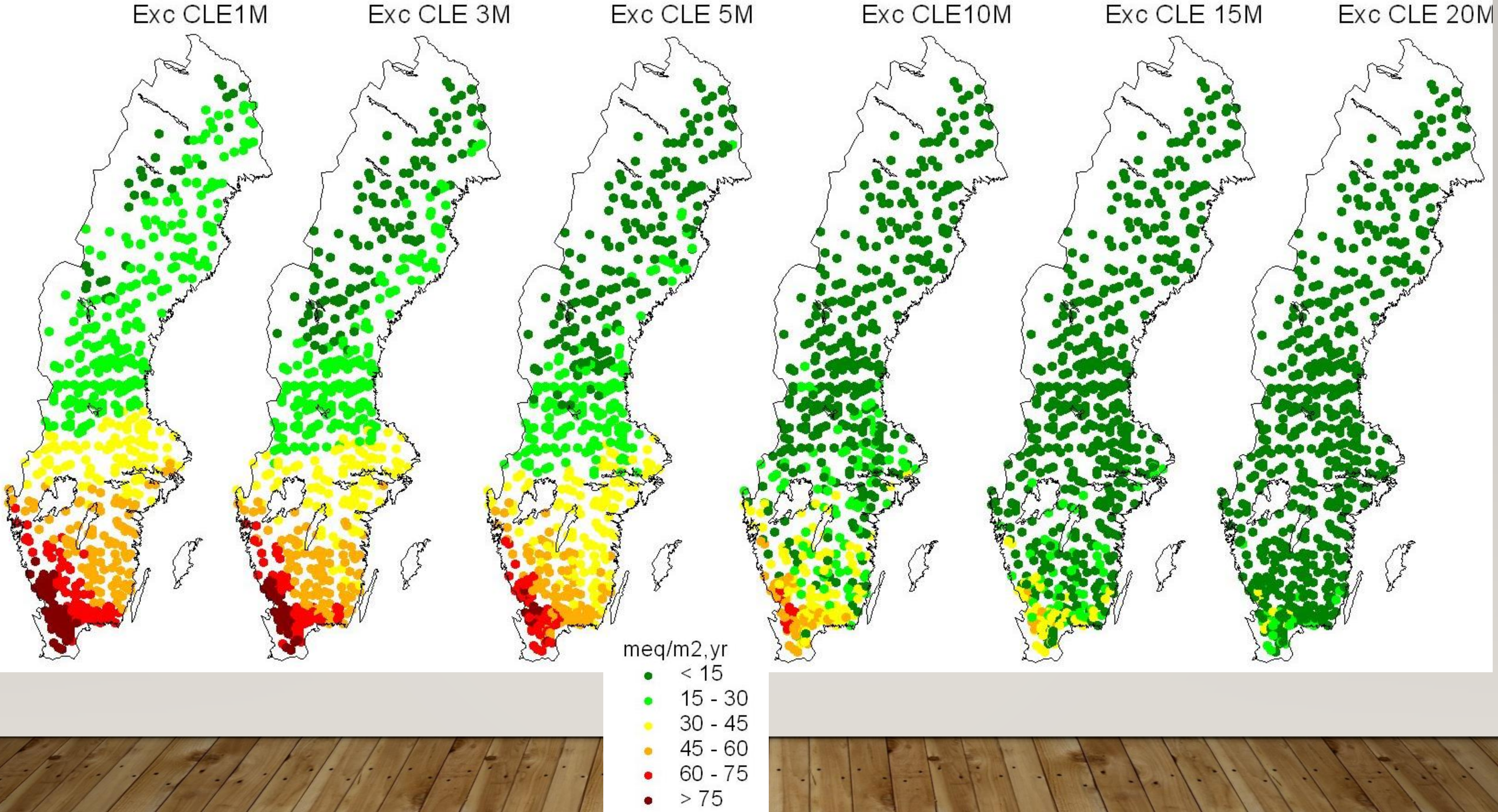


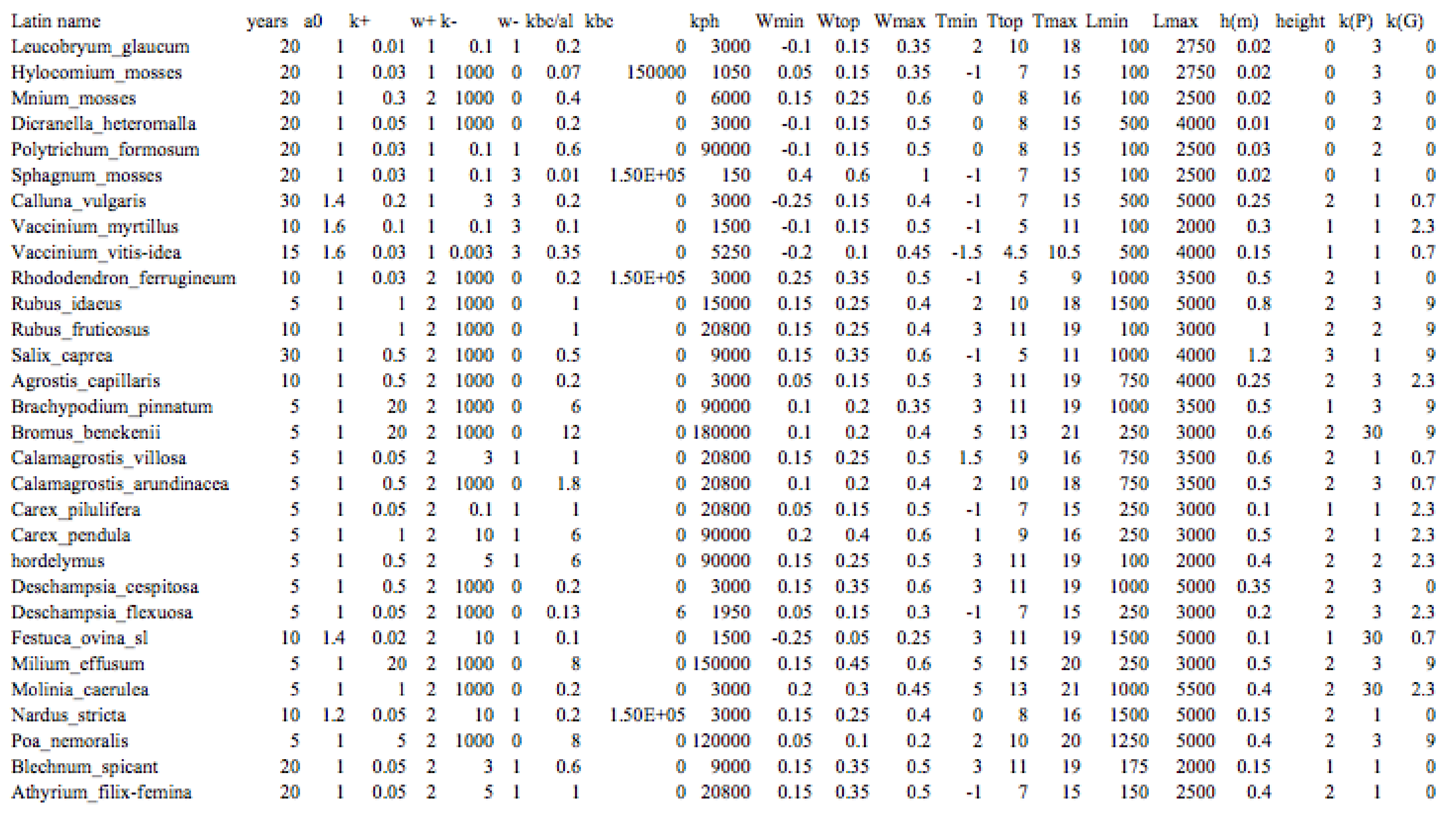
Fig. 5. Comparison of modelled and measured soil water chemistry data. The grey curves show the modelled monthly values, and the black lines the moving averages (12-month periods) of these values. ○ – measurements, and ● – yearly mean values. The dotted line and its slope reported in the equation ($y = ax$) are an indication of the discrepancy between modelled and measured data. The soil water was collected at a depth of 50 cm.

BIODIVERSITY-BASED CRITICAL LOADS FOR SWEDEN

- Based on the Swedish forestry database, using data from 27,600 sampled forest stands and using a subset of 660 sites for dynamic modelling studies. Included is climate change and long term changes in forestry.
- Checks sustainability of the forestry applied first:
  - Base cations mass balance (Mg, Ca, K)
  - Phosphorus mass balance
  - Nitrogen and carbon mass balance
- Runs biodiversity criteria, yielding critical loads for the combined effect of the following pollutants
  - Acidity
  - Nitrogen
  - Biomass harvest


Exc CLE1M
Exc CLE 3M
Exc CLE 5M
Exc CLE10M
Exc CLE 15M
Exc CLE 20M
meq/m2,yr
● < 15
● 15 - 30
● 30 - 45
● 45 - 60
● 60 - 75
● > 75

PARAMETER LIBRARY WITH 430+ PLANT TYPES



Latin name	years	a0	k+	w+	k-	w-	kbc/al	kbc	kph	Wmin	Wtop	Wmax	Tmin	Ttop	Tmax	Lmin	Lmax	h(m)	height	k(P)	k(G)
Leucobryum_glaucum	20	1	0.01	1	0.1	1	0.2	0	3000	-0.1	0.15	0.35	2	10	18	100	2750	0.02	0	3	0
Hylocomium_mosses	20	1	0.03	1	1000	0	0.07	150000	1050	0.05	0.15	0.35	-1	7	15	100	2750	0.02	0	3	0
Mnium_mosses	20	1	0.3	2	1000	0	0.4	0	6000	0.15	0.25	0.6	0	8	16	100	2500	0.02	0	3	0
Dicranella_heteromalla	20	1	0.05	1	1000	0	0.2	0	3000	-0.1	0.15	0.5	0	8	15	500	4000	0.01	0	2	0
Polytrichum_formosum	20	1	0.03	1	0.1	1	0.6	0	90000	-0.1	0.15	0.5	0	8	15	100	2500	0.03	0	2	0
Sphagnum_mosses	20	1	0.03	1	0.1	3	0.01	1.50E+05	150	0.4	0.6	1	-1	7	15	100	2500	0.02	0	1	0
Calluna_vulgaris	30	1.4	0.2	1	3	3	0.2	0	3000	-0.25	0.15	0.4	-1	7	15	500	5000	0.25	2	1	0.7
Vaccinium_myrtillus	10	1.6	0.1	1	0.1	3	0.1	0	1500	-0.1	0.15	0.5	-1	5	11	100	2000	0.3	1	1	2.3
Vaccinium_vitis-idea	15	1.6	0.03	1	0.003	3	0.35	0	5250	-0.2	0.1	0.45	-1.5	4.5	10.5	500	4000	0.15	1	1	0.7
Rhododendron_ferrugineum	10	1	0.03	2	1000	0	0.2	1.50E+05	3000	0.25	0.35	0.5	-1	5	9	1000	3500	0.5	2	1	0
Rubus_idaeus	5	1	1	2	1000	0	1	0	15000	0.15	0.25	0.4	2	10	18	1500	5000	0.8	2	3	9
Rubus_fruticosus	10	1	1	2	1000	0	1	0	20800	0.15	0.25	0.4	3	11	19	100	3000	1	2	2	9
Salix_caprea	30	1	0.5	2	1000	0	0.5	0	9000	0.15	0.35	0.6	-1	5	11	1000	4000	1.2	3	1	9
Agrostis_capillaris	10	1	0.5	2	1000	0	0.2	0	3000	0.05	0.15	0.5	3	11	19	750	4000	0.25	2	3	2.3
Brachypodium_pinnatum	5	1	20	2	1000	0	6	0	90000	0.1	0.2	0.35	3	11	19	1000	3500	0.5	1	3	9
Bromus_benekenii	5	1	20	2	1000	0	12	0	180000	0.1	0.2	0.4	5	13	21	250	3000	0.6	2	30	9
Calamagrostis_villosa	5	1	0.05	2	3	1	1	0	20800	0.15	0.25	0.5	1.5	9	16	750	3500	0.6	2	1	0.7
Calamagrostis_arundinacea	5	1	0.5	2	1000	0	1.8	0	20800	0.1	0.2	0.4	2	10	18	750	3500	0.5	2	3	0.7
Carex_pilulifera	5	1	0.05	2	0.1	1	1	0	20800	0.05	0.15	0.5	-1	7	15	250	3000	0.1	1	1	2.3
Carex_pendula	5	1	1	2	10	1	6	0	90000	0.2	0.4	0.6	1	9	16	250	3000	0.5	2	1	2.3
hordelymus	5	1	0.5	2	5	1	6	0	90000	0.15	0.25	0.5	3	11	19	100	2000	0.4	2	2	2.3
Deschampsia_cespitosa	5	1	0.5	2	1000	0	0.2	0	3000	0.15	0.35	0.6	3	11	19	1000	5000	0.35	2	3	0
Deschampsia_flexuosa	5	1	0.05	2	1000	0	0.13	6	1950	0.05	0.15	0.3	-1	7	15	250	3000	0.2	2	3	2.3
Festuca_ovina_sl	10	1.4	0.02	2	10	1	0.1	0	1500	-0.25	0.05	0.25	3	11	19	1500	5000	0.1	1	30	0.7
Milium_effusum	5	1	20	2	1000	0	8	0	150000	0.15	0.45	0.6	5	15	20	250	3000	0.5	2	3	9
Molinia_caerulea	5	1	1	2	1000	0	0.2	0	3000	0.2	0.3	0.45	5	13	21	1000	5500	0.4	2	30	2.3
Nardus_stricta	10	1.2	0.05	2	10	1	0.2	1.50E+05	3000	0.15	0.25	0.4	0	8	16	1500	5000	0.15	2	1	0
Poa_nemoralis	5	1	5	2	1000	0	8	0	120000	0.05	0.1	0.2	2	10	20	1250	5000	0.4	2	3	9
Blechnum_spicant	20	1	0.05	2	3	1	0.6	0	9000	0.15	0.35	0.5	3	11	19	175	2000	0.15	1	1	0
Athyrium_filix-femina	20	1	0.05	2	5	1	1	0	20800	0.15	0.35	0.5	-1	7	15	150	2500	0.4	2	1	0

AT HUBBARD BROOK, THE NITROGEN SIMULATIONS ARE REALLY GOOD DOWN TO DETAILS

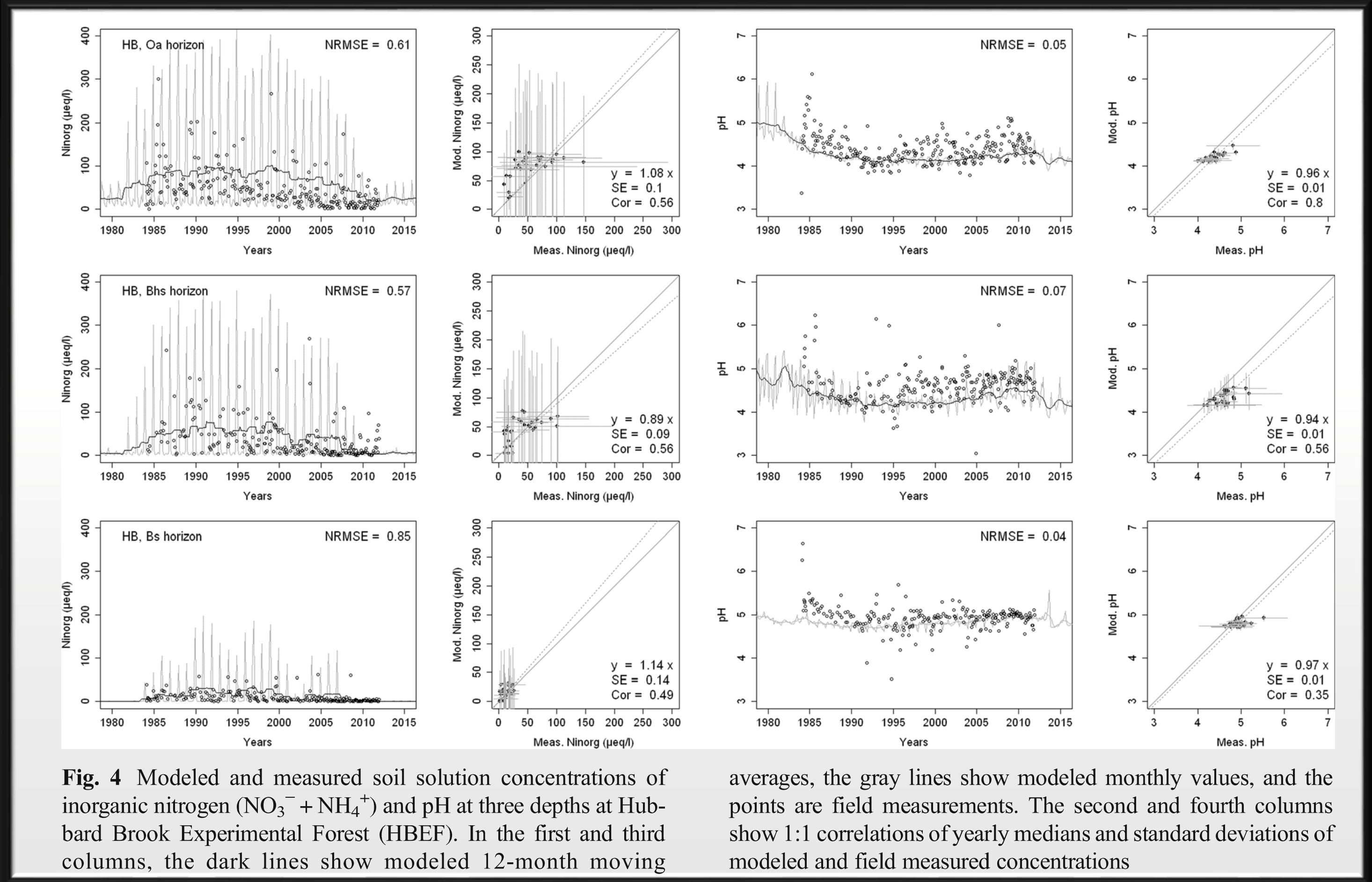
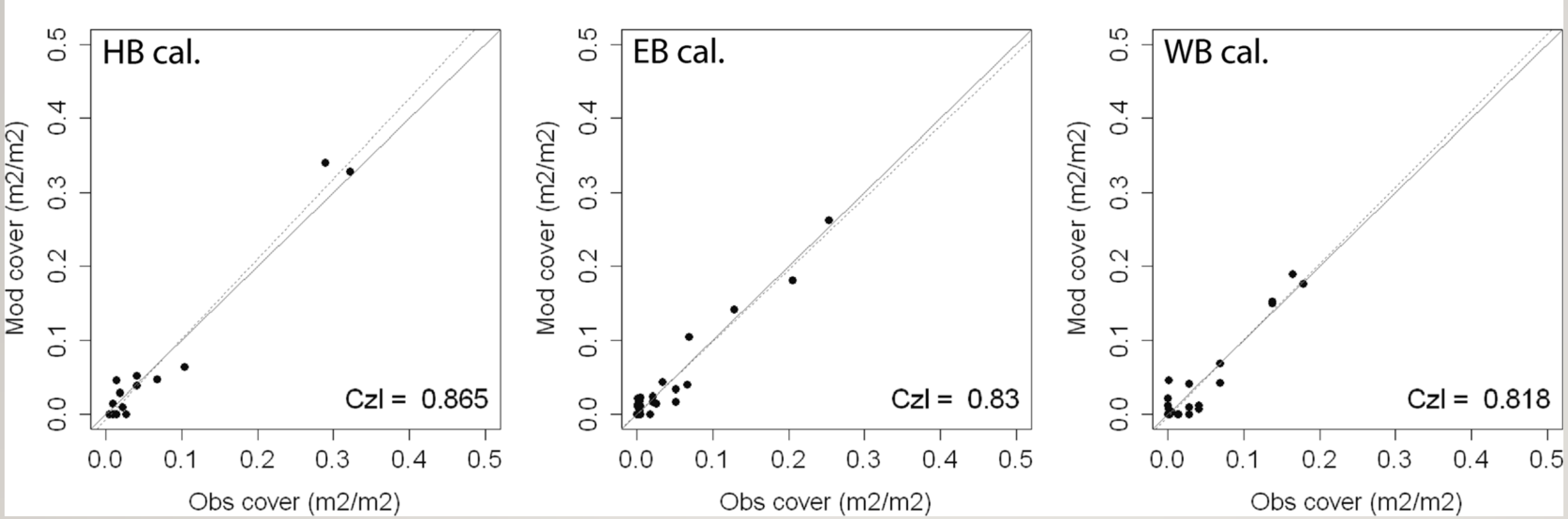
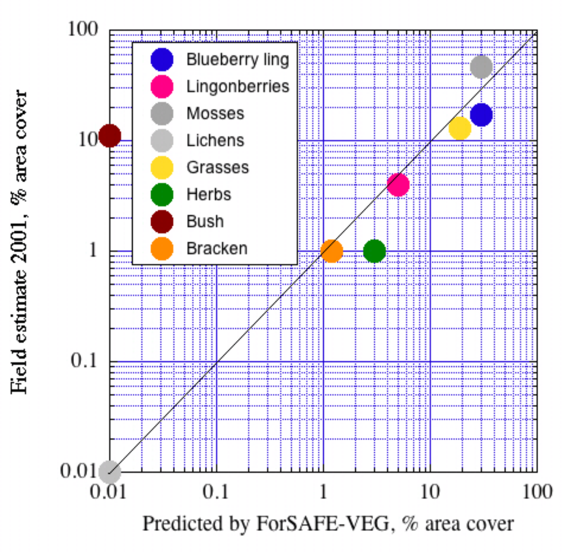


Fig. 4 Modeled and measured soil solution concentrations of inorganic nitrogen ($NO_3^- + NH_4^+$) and pH at three depths at Hubbard Brook Experimental Forest (HBEF). In the first and third columns, the dark lines show modeled 12-month moving averages, the gray lines show modeled monthly values, and the points are field measurements. The second and fourth columns show 1:1 correlations of yearly medians and standard deviations of modeled and field measured concentrations





FIELD TEST AT HUBBARD BROOK WATERSHEDS
BELYAZID ET AL., 2019

SUMMARY 1

- **Weathering**; ForSAFE weathering module was revised with expanded kinetics to include more minerals, better performance in deeper soils and groundwater. It works on profiles, slopes and for catchments relevant to trees and streams as well as in deeper groundwater.
- **Phosphorus** was successfully included into the ForSAFE-VEG system. Involves soil microorganism community and biomass. Importance for tree growth as well as ground vegetation composition. Allows accurate simulation of soil and runoff nitrogen dynamics.
- **Geometry**: ForSAFE was reconfigured to handle:
  - Soil profiles and forest stands on flat land
  - Soil profiles on slopes; Soil chemistry dynamics on slopes along flow paths, forest growth
  - Catchments and hydrology; Water chemistry entering streams from sloping watersheds.

SUMMARY II; BIODIVERSITY

- **Biodiversity**;
  - ForSAFE-2-VEG recreates the plant species distribution over space and time in sites across Sweden, Switzerland, United States of America and France with good accuracy.
  - Biodiversity-based critical loads have been mapped and published for Sweden, but have not yet been included in the Swedish National Critical Loads Reporting to the CCE.
  - We are likely to see effects in terrestrial environments long before anything is visible in the waters. The models are ready for terrestrial ecosystems, for aquatic ecosystems they are many years away. Focusing on water biodiversity instead of terrestrial is not consistent with the message from our models.

SUMMARY III

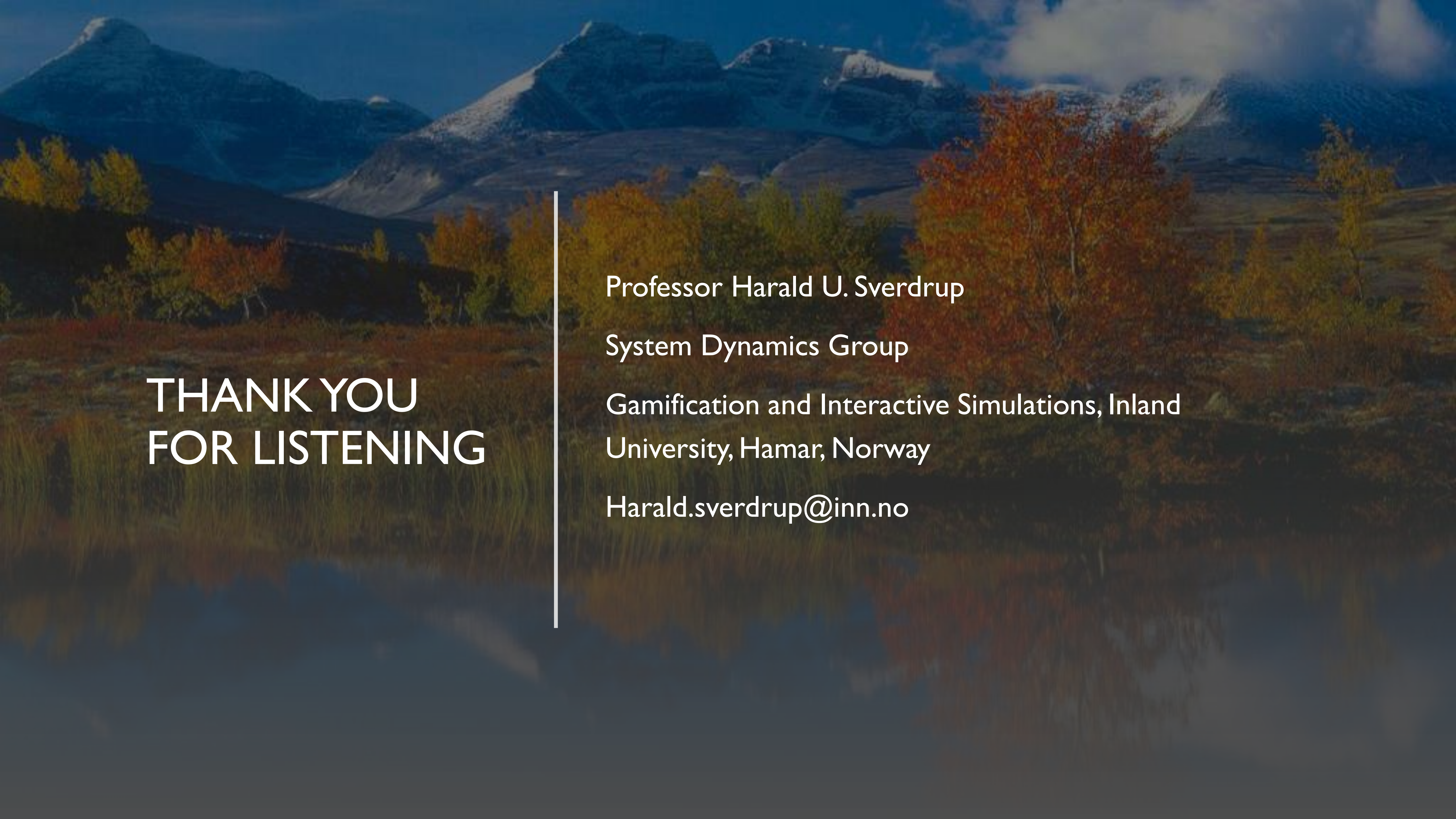
- **Climate change**
  - The simulations i ForSAFE-2 have been linked with climate change models amd the effects of cimate change on carbon cycling, soil chemistry, forest growth and biodiversity has been fully integrated (Belyazid and Zanchi 2019, Belyazid et al., 2019)
- **Tree growth and forest production** is included in the ForSAFE-2-VEG system.
  - Allows accurate simulation of tree growth, forest production and nutrient dynamics (Water balance, cations, nitrogen and phosphorus).
  - The hydrological effect on growth, eliminates the effect of increased temperature on growth and weathering
  - Regional forest production estimates.

SUMMARY 4;VALIDATION

- **Validation don**e:
  - The model works well for mapping critical loads for nitrogen and acidity based on biodiversity protection, using regional databases.
  - Biodiversity-based critical loads have been completed, validated and published for Sweden, Switzerland, United States of America and France, but have not yet been included in the Swedish National Critical Loads Reporting to the CCE.
  - Vegetation change simulations field tested and validated for United States (Rocky Mountains, New England), Sweden, Switzerland and France (Regionally, Research sites)

SUMMARY 5; POLICY FAILURES

- **Lack of funding**;
  - No funding for making critical loads for nitrogen and acidity based on biodiversity
- **Lack of priority and interest**
  - No interest in maintaining competence and willingness to prepare critical load database submissions for critical loads for acidity and nitrogen based on biodiversity
- **Loss of mometum and focus**
  - Competence is evaporating and the strategic initiatives have been lost across European Environmental Agencies. Environmental initiatives are replaced by bureucratic proceedures and minutes from meetings. The connection to large scale issues like climate change or natural resource use is not being followed up and acted on.



THANK YOU FOR LISTENING

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