Northern European Forests' carbon balance and management disturbances: the tale of the direct flux measurements

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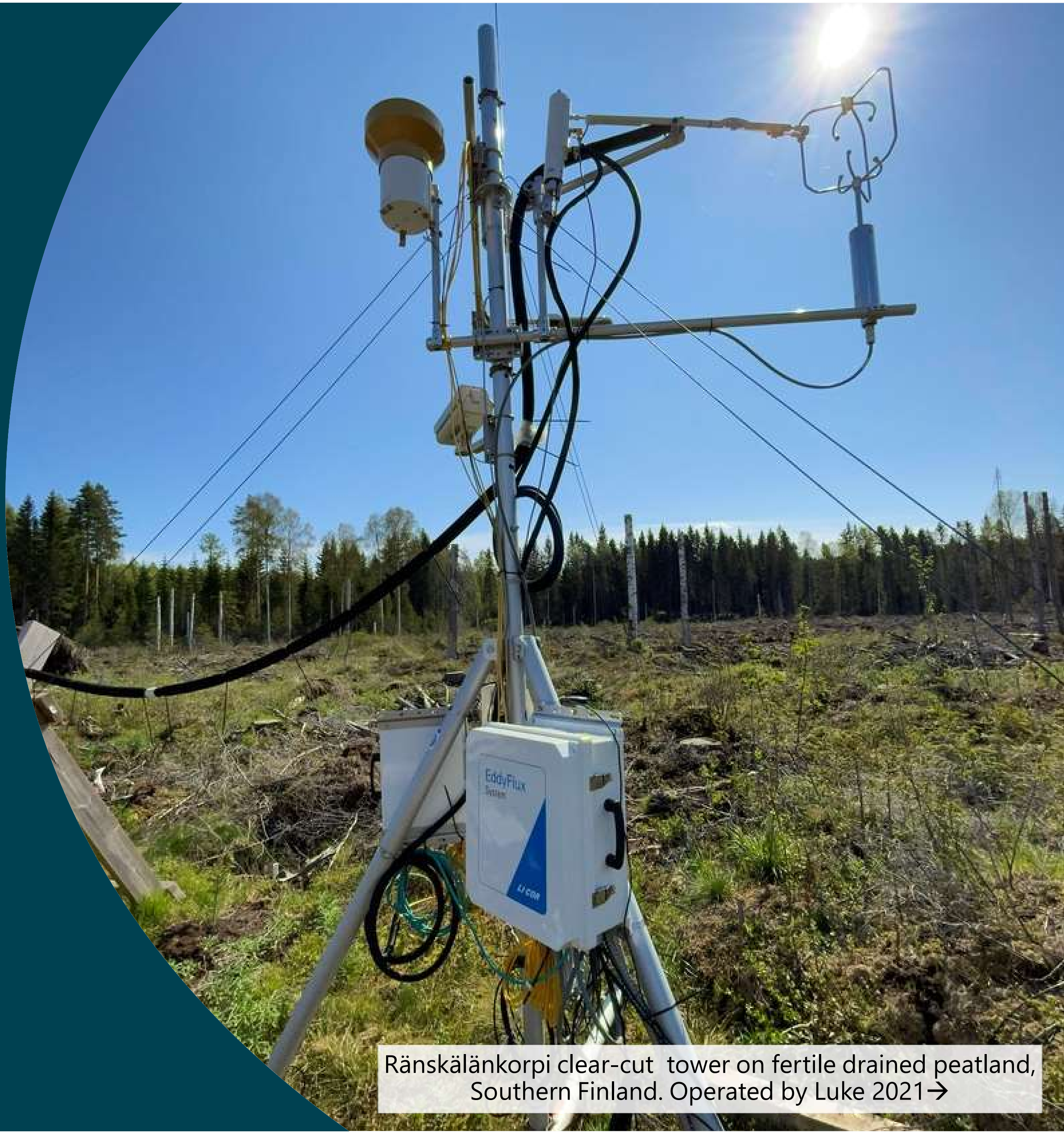


Ränskälänkorpi clear-cut tower on fertile drained peatland, Southern Finland. Operated by Luke 2021→

Why?

Forests:

✓ face multiple demands – providing carbon storage, climate regulation, income and well-being

Northern Europe:

✓ forests and forestry major land use & crucial for national climate targets

✓ Active flux community

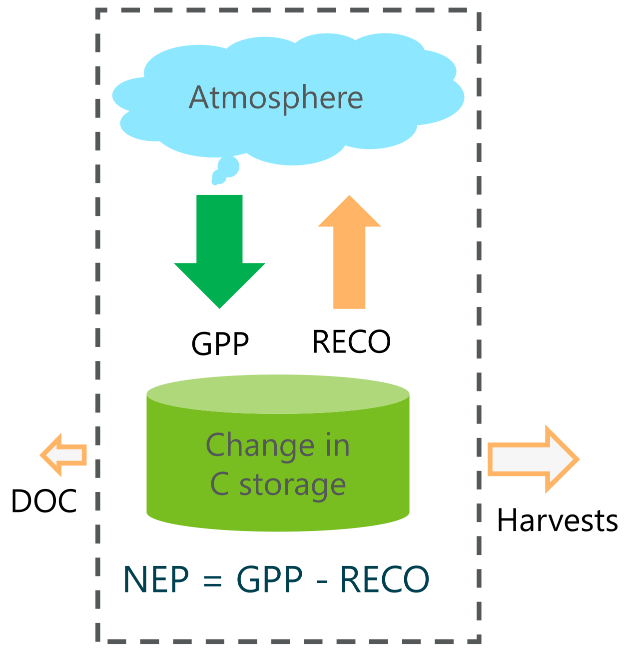
✓ Reasonably uniform – species, soils, climate, management

Synthesis:

✓ So far very few (Lindroth et al. 2008, 2020)

✓ So far only a few sites included

Ecosystem (on-site) carbon balance



Net ecosystem productivity NEP = - NEE from eddy-covariance

Ecosystem respiration RECO

- f(Temperature), inferred based on night-time NEP

Gross primary productivity GPP = NEP + RECO

What is out there?

Forest C balance by eddy-covariance?

Northern European forests	ICOS warm winter dataset FluxNet 2015 Literature review
Minimum 1 year of NEP data	Site attributes → species, (LAI), soil type, site type, management history Habitat, Köppen climate ERA5 Land → climate, gs length
Published & citable	Minimum a MSc thesis or preprint

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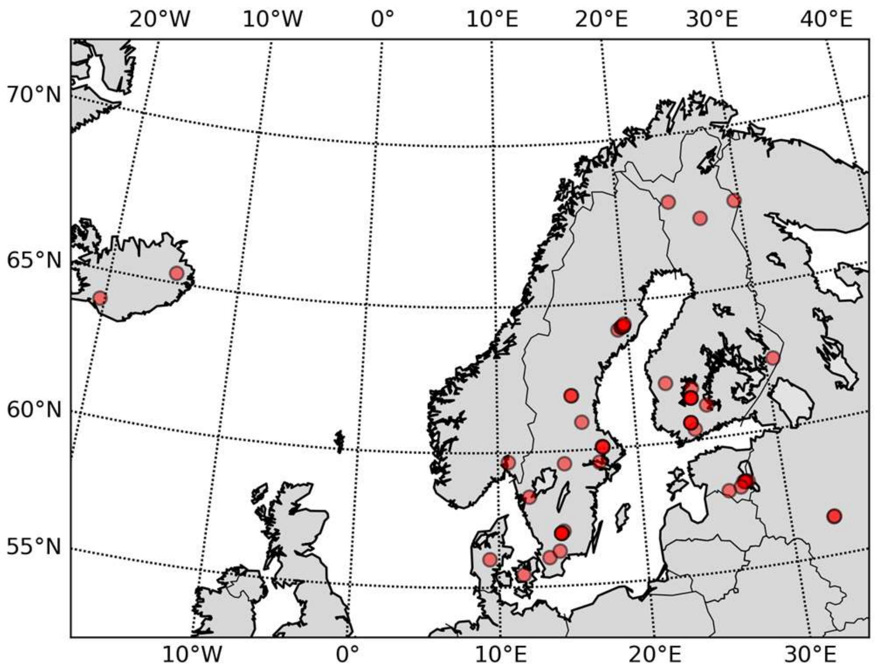
NEP:
50 sites
320 site-years
1 to 26 yr/site

GPP/RECO:
44 sites
252 site-years

1997 – 2022

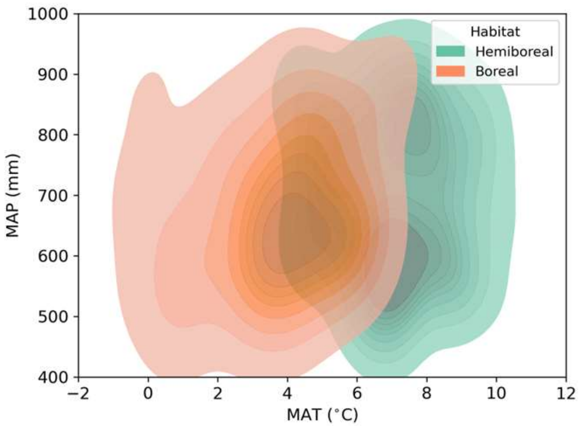


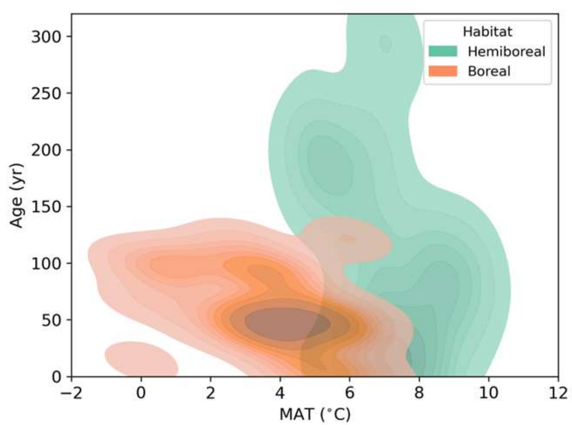
Sweden 22
Finland 15
Estonia 7
Denmark 2
Iceland 2
Russia 2
Norway 1

11 peatland forests
3 plantations
2 post-fire sites

11 recent clear-cuts
3 thinned sites
2 N-fertilization

10 ICOS warm-winter
1 Fluxnet 2015
39 Literature review





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How carbon balance vary with stand age?

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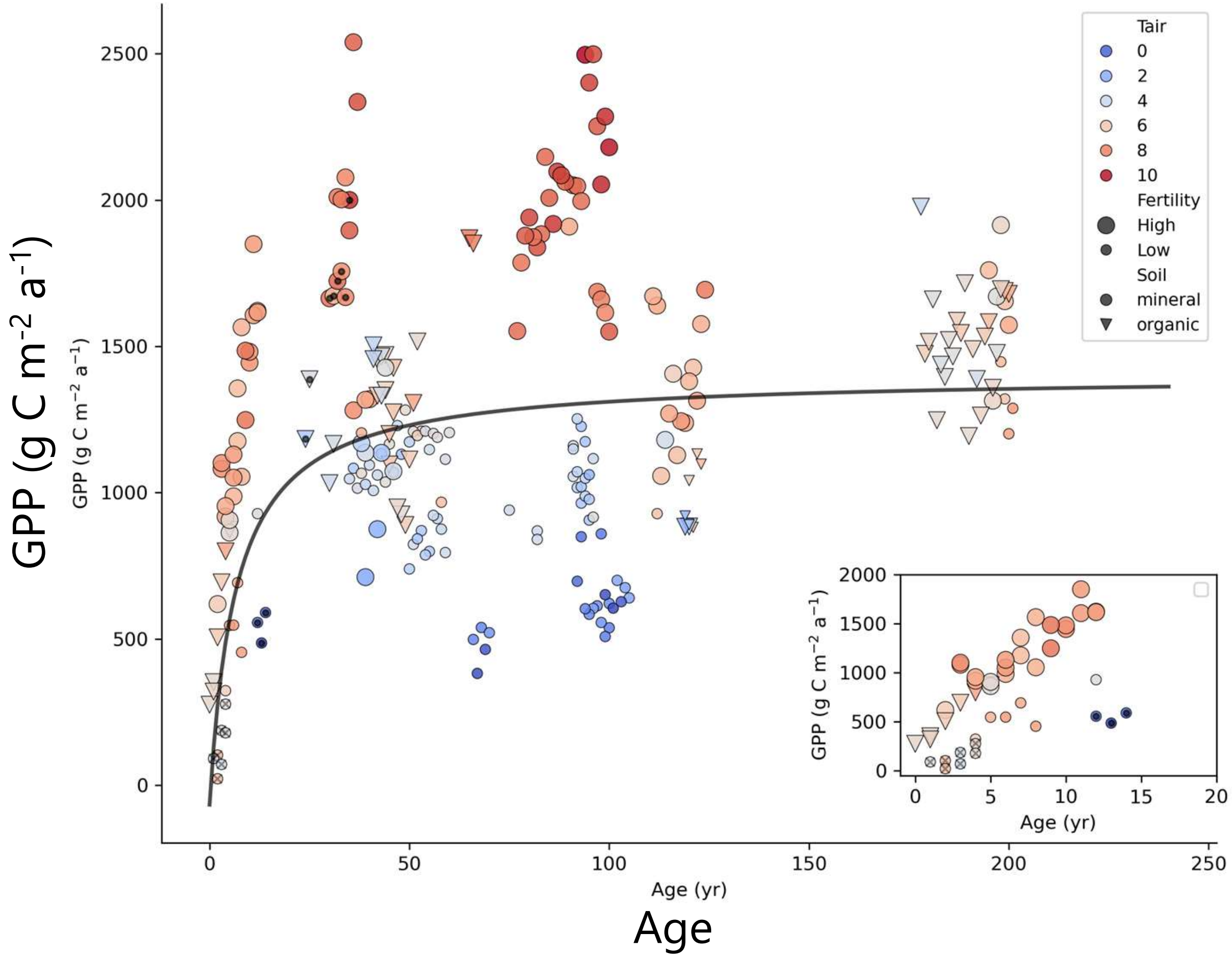
Gross-primary productivity



$$GPP = \epsilon + b \times \frac{Age}{Age + c}$$

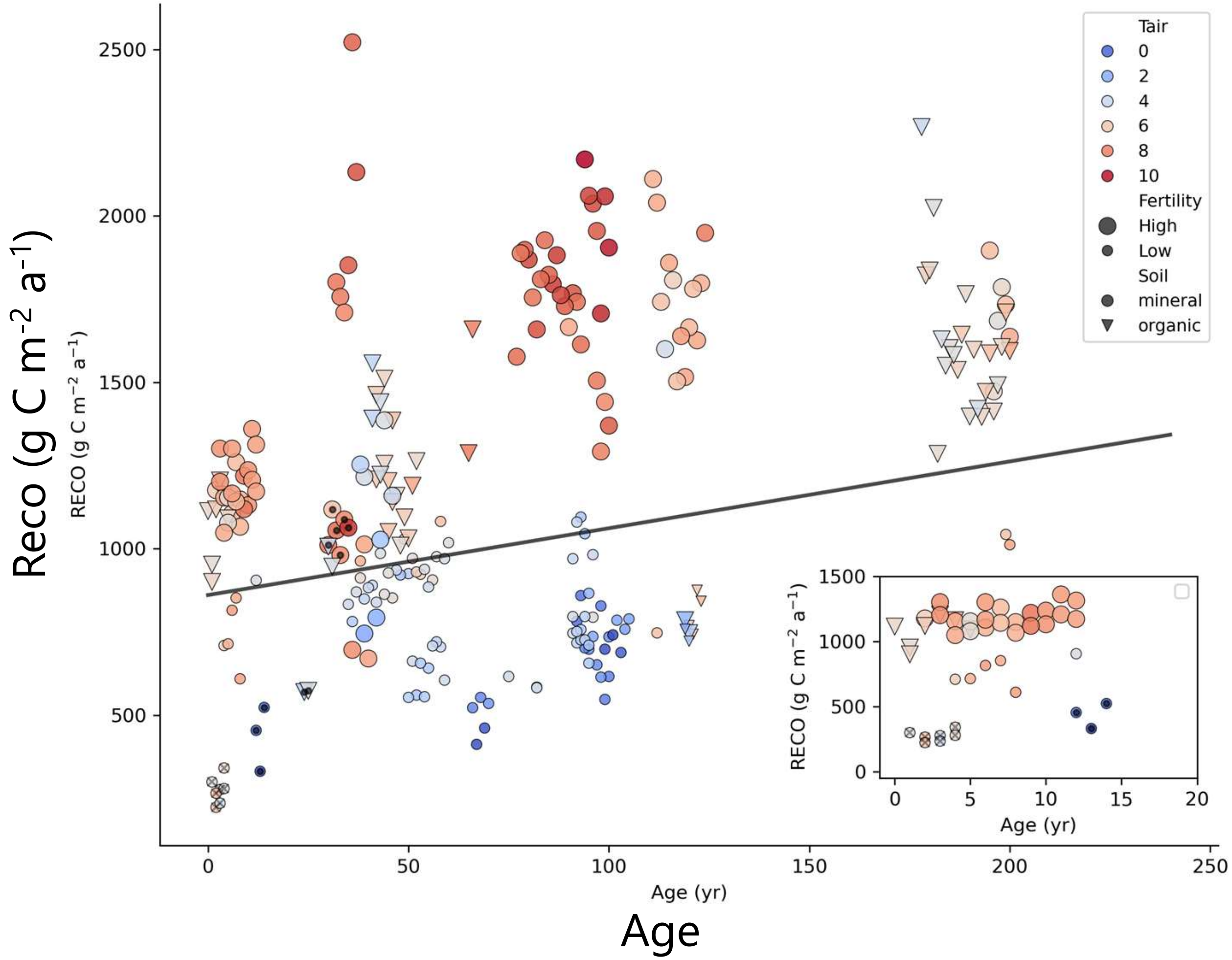
Age only: 17% of variance

Age, T_a and site attributes: 78%

$$b \propto T_a$$
$$+ VPD_{gs}$$
$$+ fertility(low)$$
$$+ habitat(hemiboreal)$$

color = MAT
size = fertility
symbol = soil type
dot = plantation
cross-hatch = post-fire

Ecosystem respiration



$$R_e = \epsilon + a + d \times Age$$

Age only: 14%

With T_a and site attributes: 71%

$$a \propto T_a$$ +

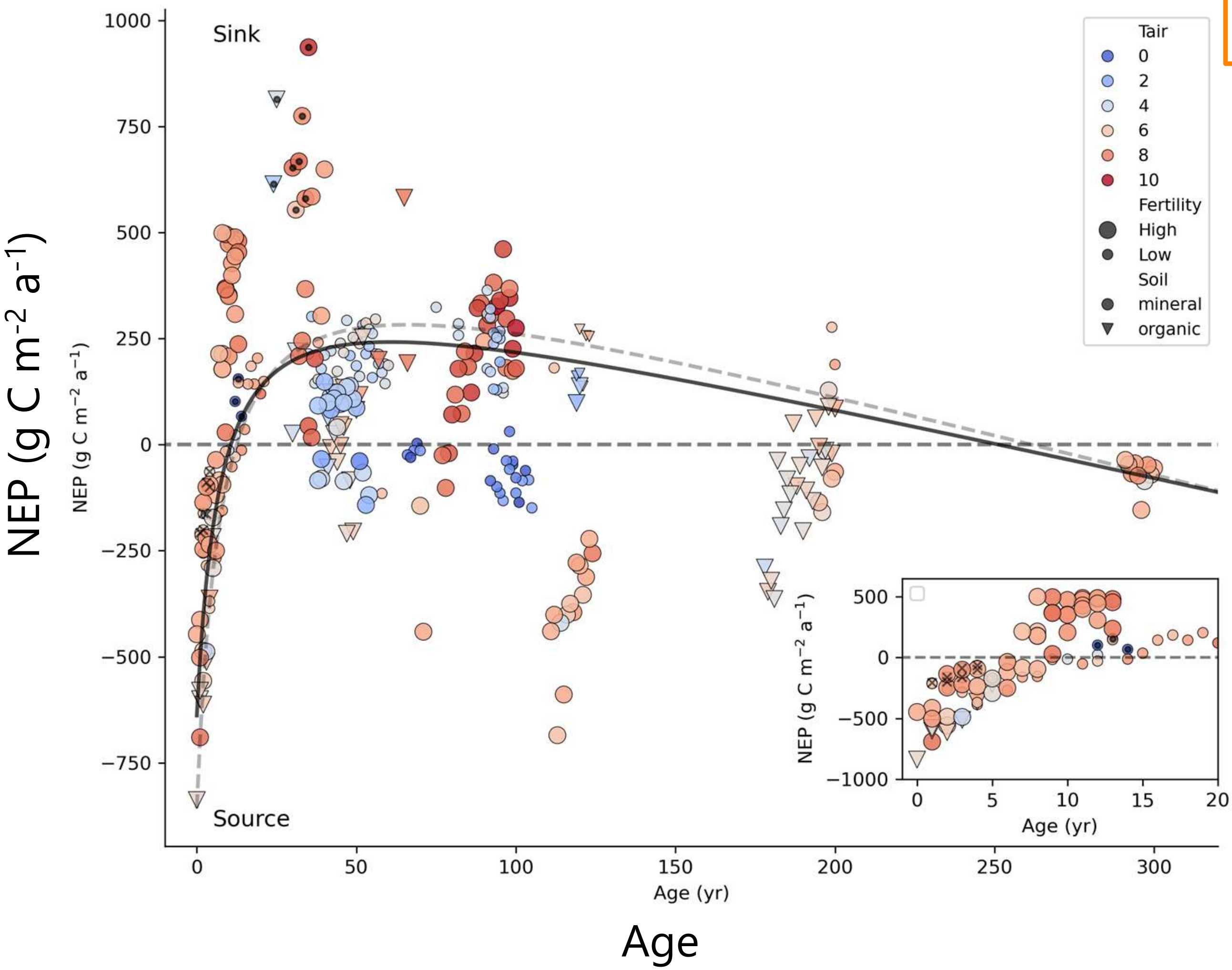
$$+ plantation\,(yes)$$ −

$$+ fertility\,(low)$$ −

$$+ habitat\,(hemiboreal)$$ +

color = MAT
size = fertility
symbol = soil type
dot = plantation
cross-hatch = post-fire

NEP – on-site carbon balance



$$NEP = \epsilon + a + b \times \frac{Age}{Age + c} - d \times Age$$

Age only: 19 % of variance

Age, T_a and plantation: 39 %

$a \propto T_a$ ✚

$+ plantation\,(yes)$ ✚

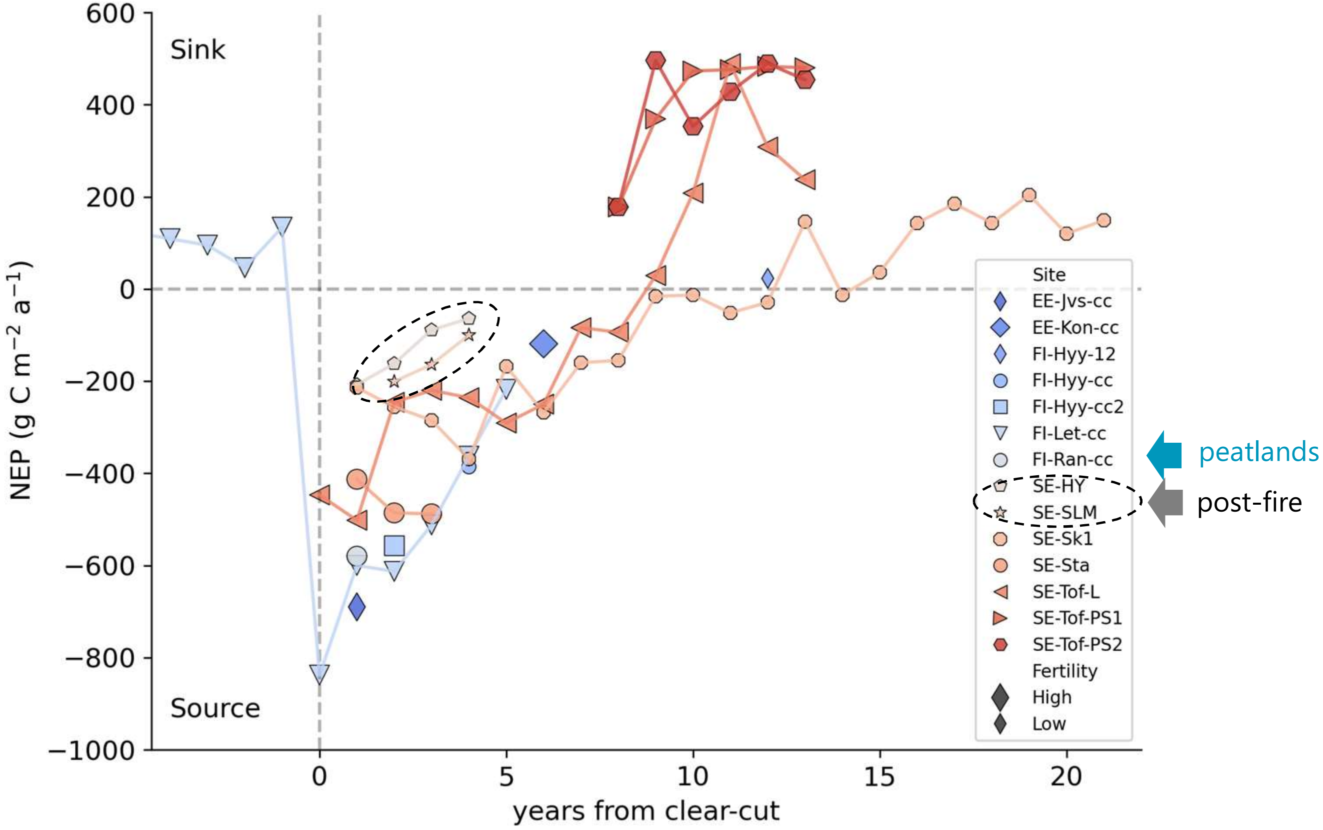
color = MAT
size = fertility
symbol = soil type
dot = plantation
cross-hatch = post-fire




How forest management practices affect C balance?

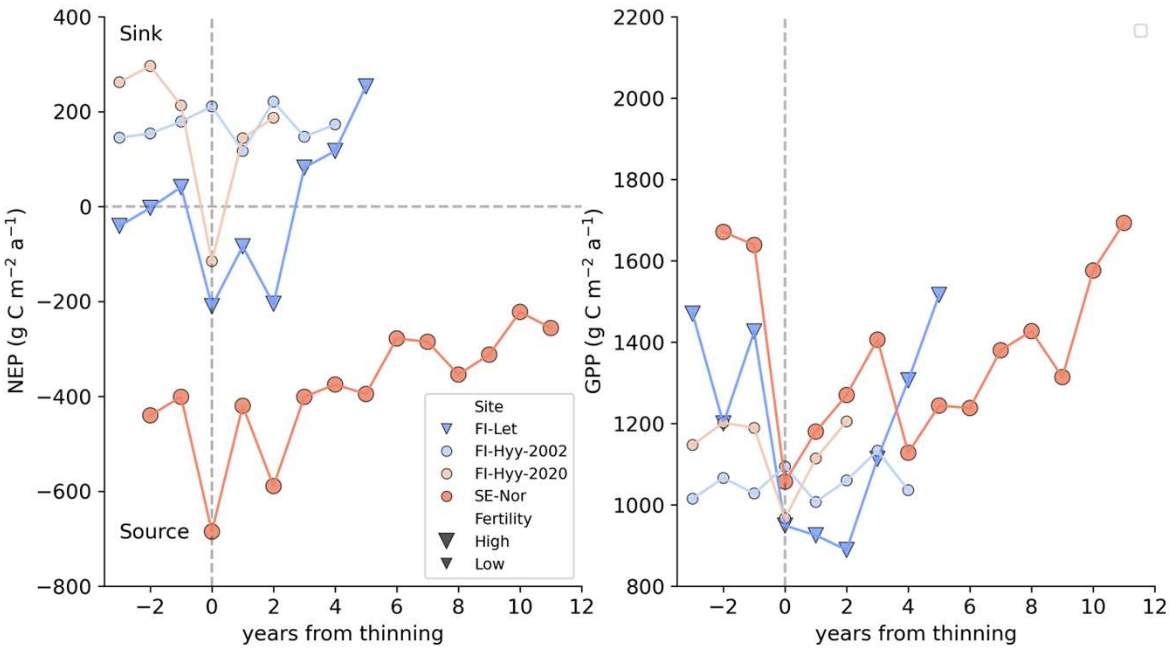
Rapid NEP recovery after clear-cutting

- ✓ From source to sink <10 year post-harvest
- ✓ Initial emissions depend on site fertility and amount & fate of cutting residues
- ✓ Significant GPP immediately after clear-cutting
- ✓ Fast GPP recovery drives NEP dynamics
  - ✓ Flush of deciduous seedlings, grass, herbs, shrubs



Kolari et al. (2004); Ahmed (2019); Korkiakoski et al. (2023); Tikkasalo et al. (2024); Kelly et al. (2024); Grelle et al. (2023, 2012); Uri et al. (2019); Rebane et al. (2024)

Thinning response is short-lived



- ✓ Short-term drop in NEP is due to GPP response
- ✓ GPP reduction (%) always smaller than removed LAI (%)
  - ✓ Light (water, nutrient) availability
- ✓ Rapid GPP and NEP recovery

- ✓ Fertile, dense stands (FI-Let & SE-Nor):
  - ✓ Reco decreases after thinning
  - ✓ Thinning improves on-site carbon sink?

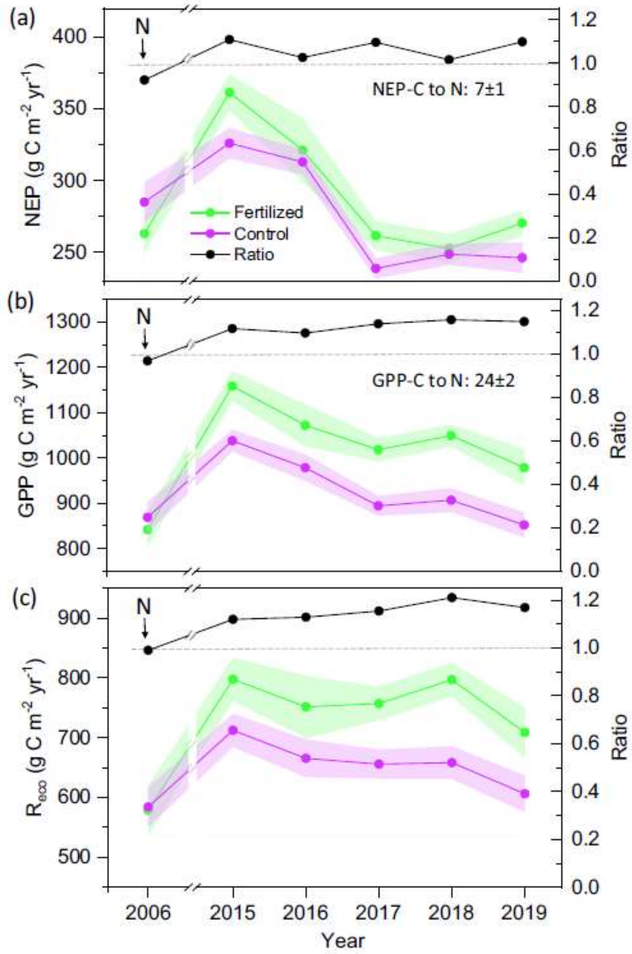
Site	Removed LAI (%)	Removed BA (m^2ha^{-1})	Site details
FI-Let	**50**	**25**	Mixed species, fertile drained peatland (Korkiakoski et al. 2023)
FI-Hyy 2002	**25**	**6**	Mixed conif., 1st thinning, infertile mineral soil (Vesala et al. 2005)
FI-Hyy 2020	**40**	**12**	2nd thinning (Aslan et al. 2024)
SE-Nor	**50**	**10**	fertile old spruce, mineral soil, high organic content (Lindroth et al. 2018)

N fertilization improves NEP

Rosinedal, N. Sweden

- ✓ Scots pine on low-fertility mineral soil
- ✓ N-fertilization 100 kg N ha^{-1} a^{-1} (2006-2011), 50-60 kg N ha^{-1} a^{-1} (2012-2019)

- ✓ Long-term N-fertilization increases both GPP and RECO.
- ✓ Small(er) positive effect on NEP



Zhao et al. (2022) Agric. For. Met.
https://doi.org/10.1016/j.agrformet.2022.109112

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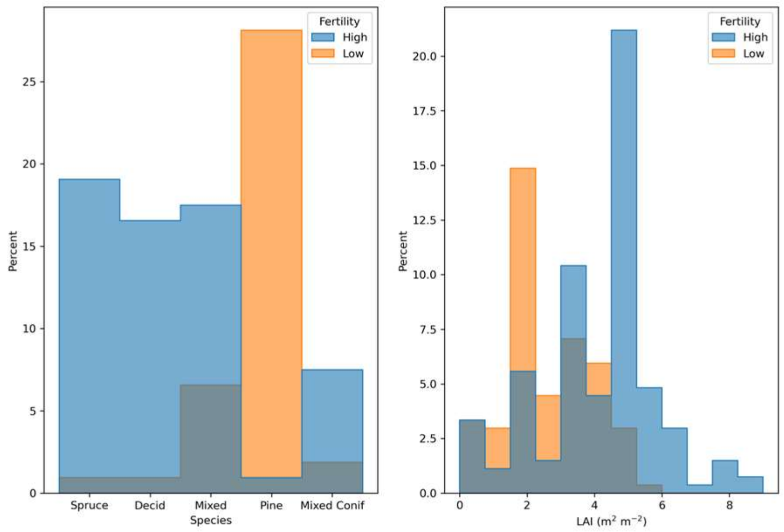
Summary – NEP, GPP and Reco variability

NEP

- ✓ Young forests strong C sources, old-growth C neutral or weak sources
- ✓ Fast recovery from stand-replacing disturbance (< 10 yrs to C neutrality)
- ✓ Soil type (mineral / organic) has no clear impact
- ✓ Low RECO and high NEP on former agric. lands / pastures → afforestation
- ✓ But - large variability

GPP and RECO

- ✓ Increase with Age & MAT (~growing season length, radiation sum...)
- ✓ High at fertile sites (~nutrients, water, species composition, LAI, soil C stock,...)



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Message – forest management

- ✓ Forestry operations act primarily on GPP
  - ✓ Rapid disturbance recovery
  - ✓ We must re-think the role of ”green slime” on C sink
- ✓ Peatland forests are not that different from mineral soil stands
- ✓ Impact to on-site C balance (NEP) only part of the story – the fate and lifetime of harvested C storage

- ✓ Three decades of flux measurements have contributed little for improving forest management

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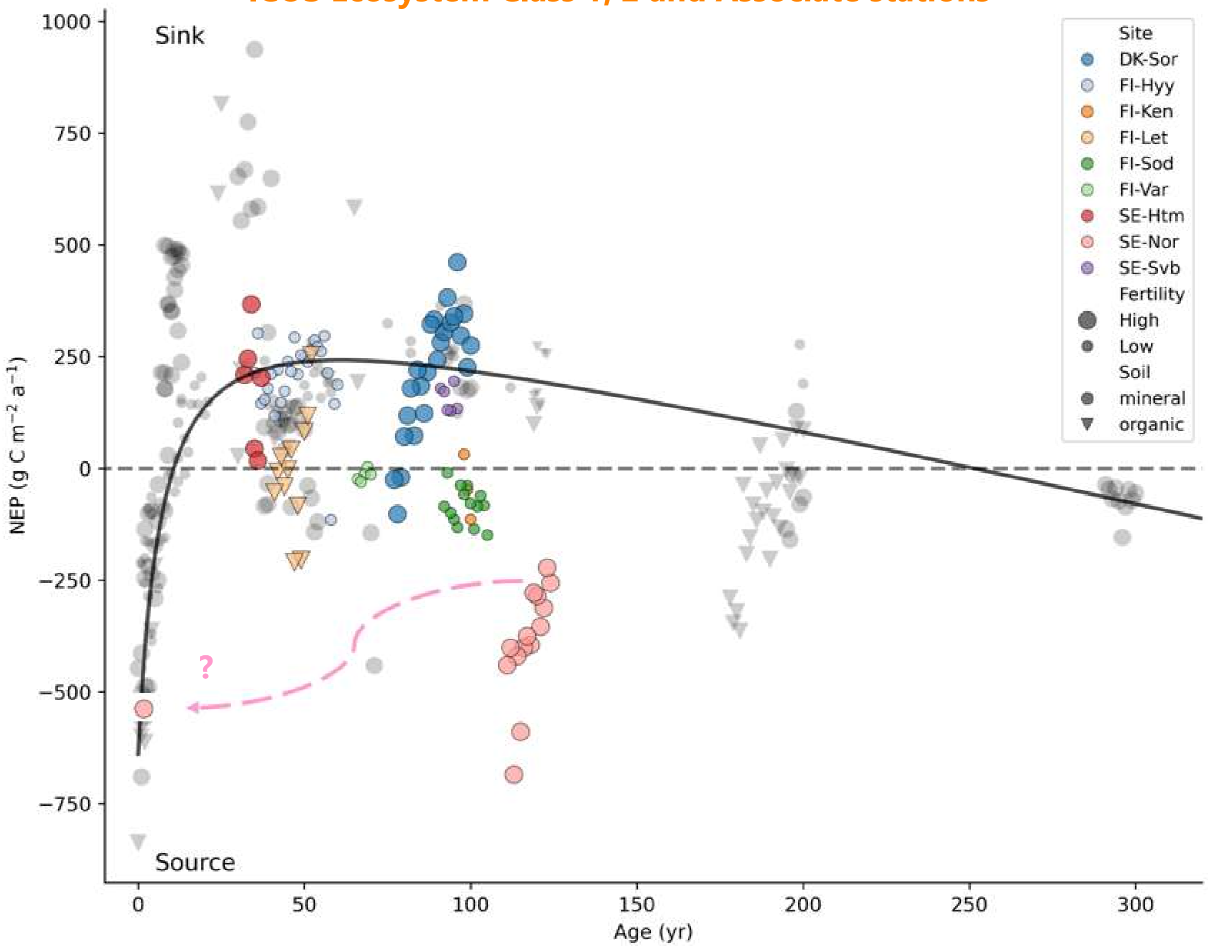
Implications – ICOS & flux community?

- ✓ Ecossystem station network == mid/late rotation coniferous forests
  - From management perspective meaningless to monitor
  - Risk of bias – C budgeting, model training, regional upscaling
- ✓ How to learn more from the few ICOS sites?
- ✓ We tend to neglect non-community studies & old data
- ✓ Combining 'Northern European Forest Flux' legacy data necessary

ICOS Ecosystem Class 1, 2 and Associate stations



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LS-Hydro (2023-2027): From forest structure to hydrological function – merging dense EO data and process-models

PREFER (2022-2026): Precision nutrient management - a tool for mitigation of climate change and environmental loading in boreal forestry

GreenFeedBack – Greenhouse gas fluxes and Earth system feedbacks

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Thank you!

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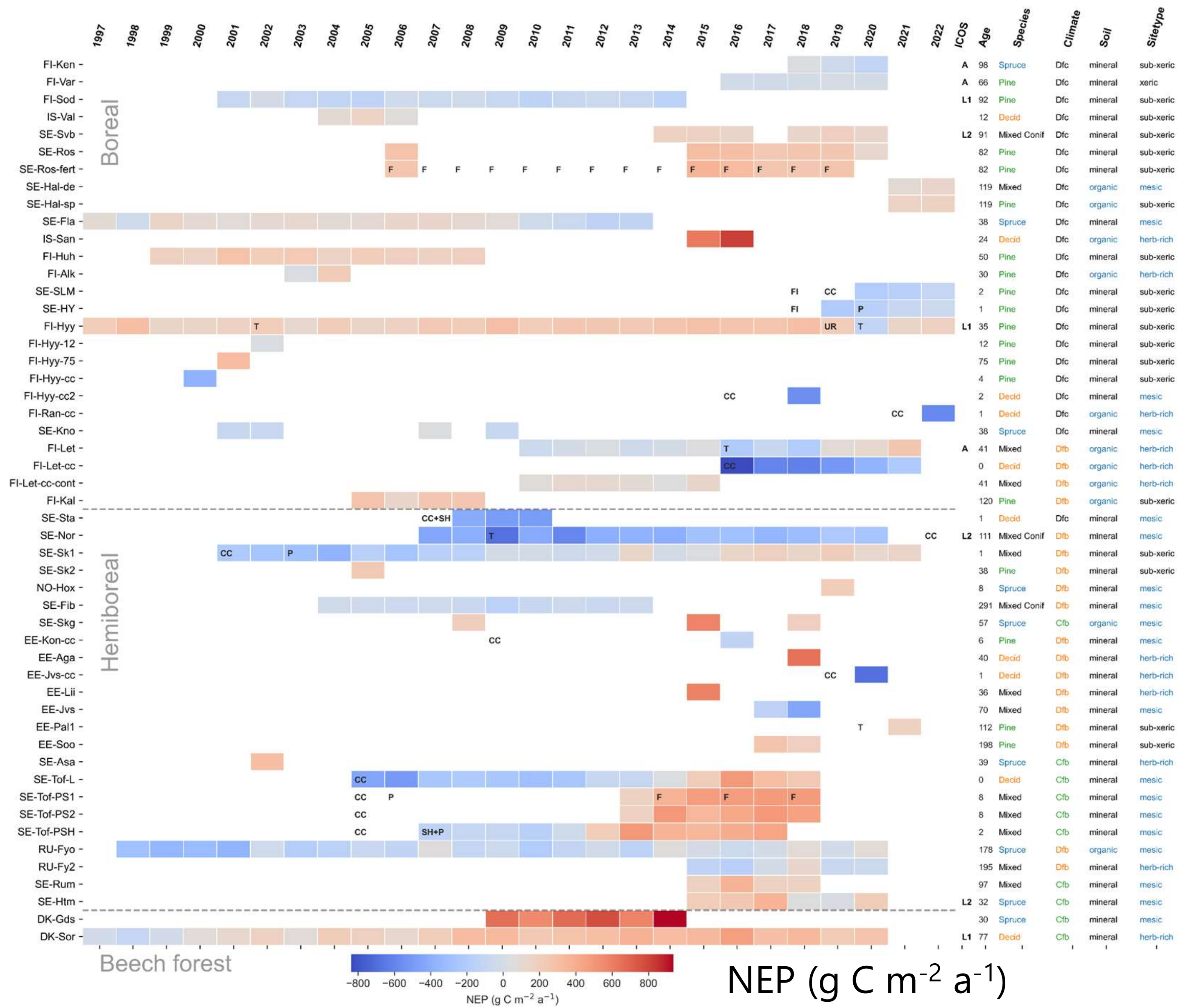

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Beech forest
FI-Ken A 98 Spruce Dfc mineral sub-xeric
FI-Var A 66 Pine Dfc mineral xeric
FI-Sod L1 92 Pine Dfc mineral sub-xeric
IS-Val 12 Decid Dfc mineral sub-xeric
SE-Svb L2 91 Mixed Conif Dfc mineral sub-xeric
SE-Ros 82 Pine Dfc mineral sub-xeric
SE-Ros-fert 82 Pine Dfc mineral sub-xeric
SE-Hal-de 119 Mixed Dfc organic mesic
SE-Hal-sp 119 Pine Dfc organic sub-xeric
SE-Fla 38 Spruce Dfc mineral mesic
IS-San 24 Decid Dfc organic herb-rich
FI-Huh 50 Pine Dfc mineral sub-xeric
FI-Alk 30 Pine Dfc organic herb-rich
SE-SLM 2 Pine Dfc mineral sub-xeric
SE-HY 1 Pine Dfc mineral sub-xeric
FI-Hyy L1 35 Pine Dfc mineral sub-xeric
FI-Hyy-12 12 Pine Dfc mineral sub-xeric
FI-Hyy-75 75 Pine Dfc mineral sub-xeric
FI-Hyy-cc 4 Pine Dfc mineral sub-xeric
FI-Hyy-cc2 2 Decid Dfc mineral mesic
FI-Ran-cc 1 Decid Dfc organic herb-rich
SE-Kno 38 Spruce Dfc mineral mesic
FI-Let A 41 Mixed Dfb organic herb-rich
FI-Let-cc 0 Decid Dfb organic herb-rich
FI-Let-cc-cont 41 Mixed Dfb organic herb-rich
FI-Kal 120 Pine Dfb organic sub-xeric
SE-Sta 1 Decid Dfc mineral mesic
SE-Nor L2 111 Mixed Conif Dfb mineral mesic
SE-Sk1 1 Mixed Dfb mineral sub-xeric
SE-Sk2 38 Pine Dfb mineral sub-xeric
NO-Hox 8 Spruce Dfb mineral mesic
SE-Fib 291 Mixed Conif Dfb mineral mesic
SE-Skg 57 Spruce Cfb organic mesic
EE-Kon-cc 6 Pine Dfb mineral mesic
EE-Aga 40 Decid Dfb mineral herb-rich
EE-Jvs-cc 1 Decid Dfb mineral herb-rich
EE-Lii 36 Mixed Dfb mineral herb-rich
EE-Jvs 70 Mixed Dfb mineral mesic
EE-Pal1 112 Pine Dfb mineral sub-xeric
EE-Soo 198 Pine Dfb mineral sub-xeric
SE-Asa 39 Spruce Cfb mineral herb-rich
SE-Tof-L 0 Decid Cfb mineral mesic
SE-Tof-PS1 8 Mixed Cfb mineral mesic
SE-Tof-PS2 8 Mixed Cfb mineral mesic
SE-Tof-PSH 2 Mixed Cfb mineral mesic
RU-Fyo 178 Spruce Dfb organic mesic
RU-Fy2 195 Mixed Dfb mineral herb-rich
SE-Rum 97 Mixed Cfb mineral mesic
SE-Htm L2 32 Spruce Cfb mineral mesic
DK-Gds 30 Spruce Cfb mineral mesic
DK-Sor L1 77 Decid Cfb mineral herb-rich
−800 −600 −400 −200 0 200 400 600 800
NEP (g C m−2 a−1)

NEP (g C m^{-2} a^{-1})