

Finnish GHG-inventory method for drained peatland forest soil net CO₂ balance - notes

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Abstract. TEXT

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1 Introduction

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5 2 The method of Alm et al. (2023)

In the current drained peatland forest soil GHG emission inventory method, the annual net CO₂ balance of peatland soil [units: g CO₂ m⁻² a⁻¹] is defined as (Alm et al., 2023)

$$F_{net} = \frac{\partial M_{CO_2}}{\partial t} = R_{Het} - \underbrace{I_{AGL} + I_{BGL}}_{F_L; \text{living plants}} - \underbrace{I_{AGR} + I_{BGR}}_{F_r; \text{residues}}, \quad (1)$$

where I_{AGL} is annual litter input flux from above-ground (living trees + ground vegetation) and I_{BGL} below ground (living trees + ground vegetation) litter input flux. These combine as litter input flux from living plants (F_L). The I_{AGR} & I_{BGR} correspond to the above and below ground litter input flux from naturally dying trees natural and harvest residues left to the site; their sum is F_r . The litter fluxes in eq. 1 are here in units [g CO₂ m⁻² a⁻¹], converted from C to CO₂ by factor $\gamma = 44/12$. The sign-convention of eq. 1 is such that negative values mean net CO₂ sink and positive values net CO₂ source, i.e. net emissions to the atmosphere.

15 The heterotrophic respiration R_{Het} [g CO₂ m⁻² a⁻¹] means emissions from decomposing organic matter, and is given as

$$R_{Het} = \underbrace{D_P + D_{AGL} + D_{BGL}}_{F_{dec}; \text{peat \& litter}} + \underbrace{D_{AGR} + D_{BGR}}_{F_{dec,r}; \text{residues}}, \quad (2)$$

where D_P is flux from decomposition of old peat and, D_{AGL} & D_{BGL} CO₂ flux from decomposition of litter from living plants (1), and D_{AGR} & D_{BGR} that from dead plants and cutting residues left at the site (eq. 1).

The annual litter fluxes are proportional to living tree and understory biomass, natural mortality and harvests. They are
 20 estimated from measured national forest inventory (NFI) variables and harvest statistics as detailed in Alm et al. (2023).

Combining eq. 1 and 2 yields

$$CO_{2,Net} = \frac{\partial M_{CO_2}}{\partial t} = - \underbrace{(I_{AGL,trees} + I_{GW} + I_{froot})}_{I: F_L} + \underbrace{(D_P + D_{AGL} + D_{BGL})}_{II: F_{dec}} + \underbrace{-(I_{AGR} + I_{BGR}) + (D_{AGR} + D_{BGR})}_{III: F_{net,r} = -F_r + F_{dec,r}}, \quad (3)$$

where $I_{AGL,trees}$ is above-ground and coarse root litter input from living trees, I_{GW} from ground vegetation, and I_{froot} the
 influx from fine root litter. The terms $I - III$ and their components arise from the conceptualization of the soil CO_2 balance
 25 calculation in Alm et al. (2023) (see Fig. ??). There are fundamental differences how each term is estimated, and the underlying
 assumptions are next briefly discussed.

2.1 Litter inputs estimated from NFI attributes (Term I) and harvest statistics (Term III)

The basic computational unit for $CO_{2,Net,j,k}$ [g CO_2 m⁻² a⁻¹] is a distinct peatland site fertility type (j) in a given climate
 (i.e. geographical location k ; Southern and Northern Finland inventory regions). The site fertility type (FTYPE) has five levels,
 30 ranging from fertile herb-rich (*Rhtkg*) to nutrient poor *Cladonia* (*Jatk*) site, and their areas can vary with time (Fig. 1. The
 litter input from living trees $I_{AGL,trees}$ (excluding fine roots) is the sum of mean tree component biomasses (e.g. leaf/needle,
 branch, bark, stem, coarse roots) multiplied by their respective turnover rates (Alm et al. (2023), Table 5). The tree component
 biomasses at FTYPE level for the inventory regions are computed from NFI data (Alm et al., 2023): "*Biomasses are calculated*
 35 *by multiplying mean stem volume in each FTYPE with biomass conversion and expansion factors (BCEFs) based on biomass*
models of Repola (2008, 2009). BCEFs are component biomass to stem volume ratios, estimated using a subsample of trees
measured in detail in each NFI for all different combinations of tree species group, FTYPE, and south and north region.".
 Same organ-specific turnover rates are used at all site types (Alm et al. (2023), Table 5). Fig. 2 shows timeseries of mean basal
 areas and litter input from living trees (excl. fine roots).

The ground vegetation (GW) litter input (I_{GW} [g CO_2 m⁻² a⁻¹], excluding fine roots of dwarf shrubs) is estimated as
 40 decreasing function of stand basal area (BA), [m² ha⁻¹]:

$$I_{GW} = 0.5 \gamma (a_{0,j} + a_1 BA) \quad (4)$$

at site-type level (j) level; $a_{0,j}$ [g DM m⁻² a⁻¹] is site-type dependent baseline litter input, and $a_1 = -4.52$ [g DM m⁻² a⁻¹ /
 (m² ha⁻¹) BA] the response to BA (Alm et al. (2023), Table 4 & eq. A3), and 0.5γ convert dry mass to CO_2 .

The fine root litter input (I_{root} [g CO_2 m⁻² a⁻¹], combined for living trees and dwarf shrubs) is estimated as the product of
 45 fine root biomass and turnover rate (Alm et al. (2023), Table 3 & 6)

$$F_{root,j,k} = 0.5, \gamma \tau_j M_{root,k} = \gamma \tau_j (b_{0,k} + b_1 BA_{spruce} + b_2 BA_{decid} + b_3 f_{shrub,j}), \quad (5)$$

where k is region, j is site type and $f_{shrub,j}$ [%] site type specific mean areal coverage of dwarf shrubs (Alm et al. (2023),
 Table 3). While $M_{root,k}$ is same for all site fertility types, the turnover rates τ_j vary from 0.8 (herb-rich *Rhtkg*) to 0.2 (nutrient

poor *Vatkg*, *Jatkg*) (Alm et al. (2023), Table 6 & eg. A4). Additional litter input from harvest residues (F_r) is computed based on harvest statistics and fate of cutting residues (harvested for bioenergy vs. left to the site) from drained peatlands. Litter production from trees that had died naturally is derived from NFI, and is available at regional scale. Latter in the paper, we refer the sum of cutting residues and naturally died tree litter as 'residues'.

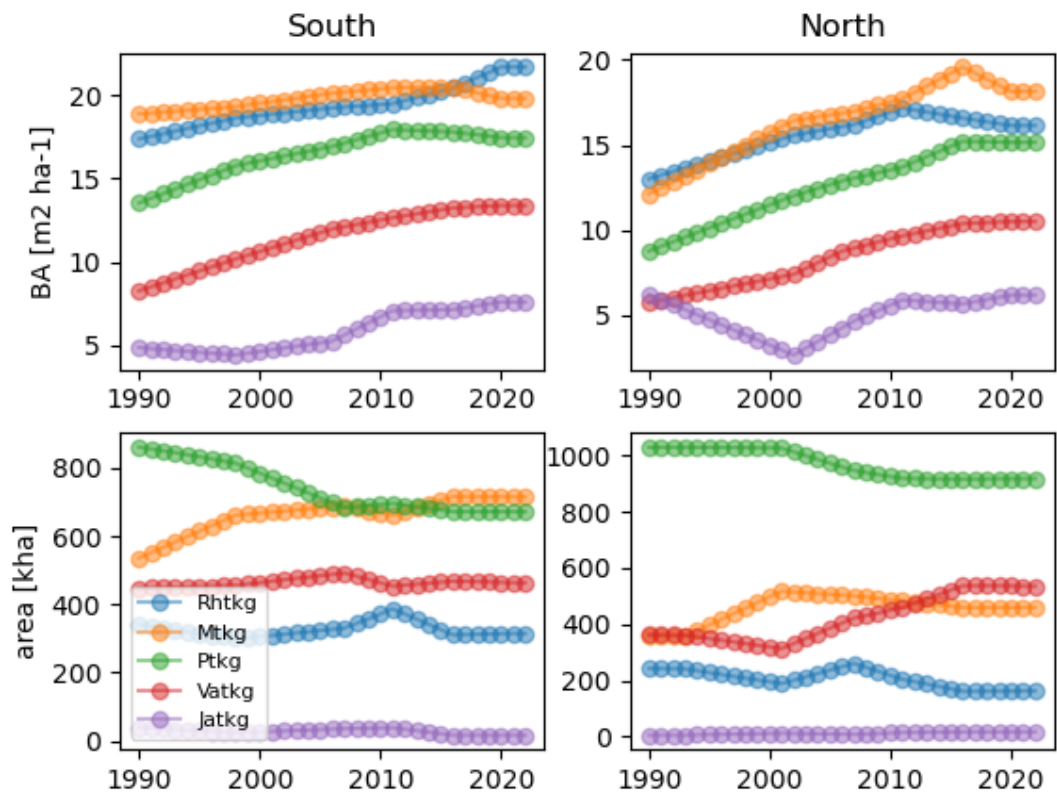


Figure 1. Mean basal areas (BA) and area of peatland fertility types in Southern & Northern Finland inventory region. Data from Alm et al. (2023) Zenodo supplementary.

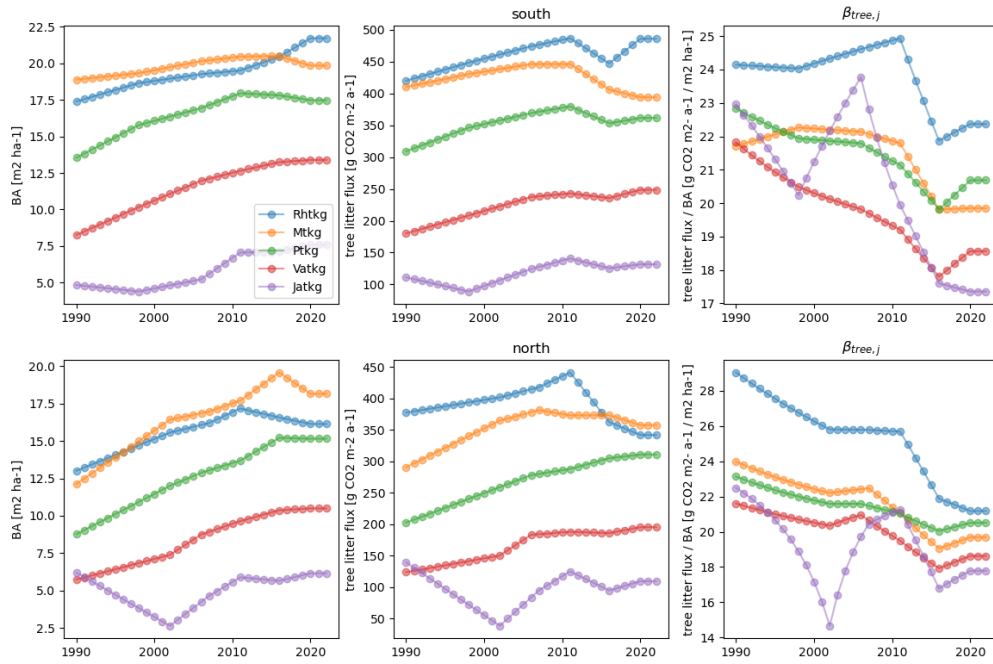


Figure 2. Basal areas (BA), annual litter input flux from living trees (excl. fineroots), and the ratio of tree litter flux and BA. See Fig. A1 & A2 for species-specific BA's and litter fluxes. Data from Alm et al. (2023) Zenodo supplementary.

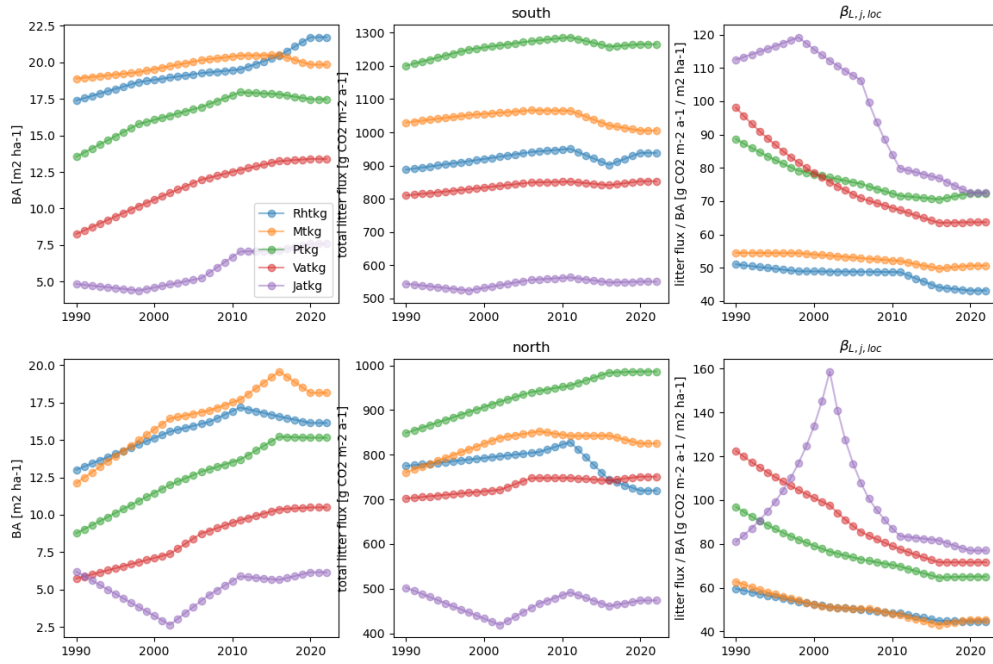


Figure 3. Basal areas (BA), annual total litter input flux (living trees, ground vegetation and fineroots), and the ratio of tree litter flux and BA ($\beta_{j,k}$). Data from Alm et al. (2023) Zenodo supplementary.

2.2 Soil CO₂ balance without residues

Soil $F_{net,j}(t)$ without cutting residues at year t is the sum of Term I and II :

$$55 \quad F_{net,j}(t) = -F_{L,j}(t) + F_{dec,j}(t), \quad (6)$$

where F_L [g CO₂ m⁻² a⁻¹] is the litter influx, and negative balance means net soil CO₂ sink.

Decomposition of old peat and litter from living plants is computed with a lumped linear model Ojanen et al. (2014)

$$F_{dec} = \alpha_{0,j} + \alpha_1 BA + \alpha_2 T_{gs}, \quad (7)$$

where $\alpha_{0,j}$ [<0 , g CO₂ m⁻² a⁻¹] is site-type dependent constant (at $BA = 0$ & $T_{gw}=0^\circ\text{C}$) and $\alpha_1=14.74$ [g CO₂ m⁻² a⁻¹ ha m⁻²] & $\alpha_2=242.8$ [g CO₂ m⁻² a⁻¹ degC⁻¹] sensitivities to stand BA and 30-year running average growing season (T_{gs}) air temperature. The positive α_1 is interpreted through increasing depth of oxic layer due to deeper water table (WTD) in dense stands (Alm et al., 2023), but can likewise be interpreted as (implicitly) enhanced decomposition with increasing litter input.

The temperature term lumps the direct temperature response of decomposition, and assumed positive relationship with T and WTD (i.e. increasing T_{gs} deepens water table, Alm et al. (2023)).

65 Describing F_L proportional to BA (see Fig. 3), eq. 7 becomes

$$F_{net,j} = -\beta_{j,k}(BA) \times BA + (\alpha_{0,j} + \alpha_1 BA + \alpha_2 T_{gs}), \quad (8)$$

where $\beta_{j,k}(BA)$ is the peatland-type and region depended litter production to BA -ratio. Fig. 3 (right column) suggest $\beta_{j,k}(BA)$ is a non-linearly decreasing function of BA. The exact form should be derived directly from allometric equations or stand level growth models and turnover rates (see latter ideas), rather than relying on biomass expansion factors based on peatland-type specific regional average stem volumes (see prev. sect).

Assuming F_L is linearly proportional to BA, re-organizing yields

$$F_{net,j,k} = \alpha_{0,j} + (\alpha_1 - \beta_{j,k}) BA + \alpha_2 T_{gs}. \quad (9)$$

Based on Fig. 2, the median values for $\beta_{j,k}$ for 1990-2020 period range from 49 (at RHtkg in South) to 106 (at Jatkg in South), while in the current forest state (median of the last 5 years) $\beta_{j,k}$ range from 43 to 72.

75 Eq. 9 provides a convenient framework to explore the sensitivity of soil CO₂ balance to BA and T_{gs} , and to consider whether the current GHG inventory model correctly reflects the effects of hydrometeorological trends and the interplay between forest structure and WTD on soil net CO₂ balance. The effect of BA on $F_{net,j,k}$ now depends on $(\alpha_1 - \beta_{j,k}) < 0$, meaning managing for increased basal area (postponed harvests, improved growth by fertilization) can have indirect favorable effect on soil carbon storage. The temperature term, however, is independent of BA and thus on any management.

80 Budgets and sensitivities of eq. 7 & 9 at current temperature and forest state are evaluated in Fig. 4.

Can we formulate whole peatland forest C balance into a simplified analytical equation by extending eq. 9? $\partial M_c / \partial t = f(BA, t)$; see notes in pdf.

region	peat_type	T _{gs} (°C)	BA (m ² ha ⁻¹)	Heterotrophic respiration, eq. 7				Soil CO ₂ balance (eq. 9)		
				R _{het} (g CO ₂ m ⁻² a ⁻¹)	Q ₁₀ (-) dT=1°C	dR _{het} /dBA (% / 1 m ² ha ⁻¹)	dR _{het} /dT _{gs} (% / 1°C)	NEEs (g CO ₂ m ⁻² a ⁻¹)	dNEEs/dBA (% / 1 m ² ha ⁻¹)	dNEEs/dT (% / 1°C)
south	Rhtkg	11.7	21.7	1777.6	3.6	0.8	13.7	840.4	-3.4	28.9
south	Mtkg	11.6	19.8	1668.3	3.9	0.9	14.6	665.1	-5.4	36.5
south	Ptkg	11.3	17.5	1339.6	5.3	1.1	18.1	73.1	-78.8	332.1
south	Vatkg	11.3	13.4	1170.2	6.6	1.3	20.7	316.8	-15.4	76.6
south	Jatkg	11.2	7.6	1017.4	8.5	1.4	23.9	465.7	-12.4	52.1
north	Rhtkg	10	16.1	1282.3	5.7	1.1	18.9	564.3	-5.3	43.0
north	Mtkg	10.1	18.2	1280.5	5.7	1.2	19.0	453.4	-6.8	53.6
north	Ptkg	9.9	15.2	965.8	9.4	1.5	25.1	-23.4	-214.7	1035.5
north	Vatkg	9.9	10.5	787.5	14.7	1.9	30.8	35.9	-158.3	676.3
north	Jatkg	10.4	6.2	802.5	14.1	1.8	30.3	325.4	-19.1	74.6

Figure 4. Heterotrophic respiration (R_{het} , eq.7) and soil CO₂ balance (NEEs, eq.9) and their relative sensitivities to basal area (BA) and growing-season temperature (T_{gs}). The numbers represent and sensitivities are computed at current BA and T_{gs} for each region and peatland type. R_{het} linear temperature sensitivity (eq. 7) is further converted to the conventional $Q_{10} = \left(\frac{R_2}{R_1}\right)^{(10/(\Delta T))}$. Q_{10} is here evaluated with $\Delta T = 1^\circ C$, which is factor of 2 larger than temperature increment during the 33 year period in Alm et al. (2023). Thus, the Q_{10} would be even larger for smaller ΔT . For biological processes, such as decomposition, typical Q_{10} is 2–3.

Use models (Motti, Susi) to derive shape of annual volume / biomass growth as a function of BA. Likewise, mortality is proportional to BA, harvests proportional to BA (external pressure). Litter input is then trivial, as currently. For *decomposition*, we develop alternative 'hypotheses' / conceptualizations, and ask how i) different peatland C balance is, ii) how means and trends vary, iii) which alternative formulation best reflects ecology and management knowledge of peatland forests. Again here, let's use Susi, Spafhy-Peat etc. simulations to create WTD as function of BA - T - drainage spacing etc... or Yasso / ESOM-style simulations and aggregate them into simple one-pool equation (cohort model?) that can be solved analytically. Inventory aggregates stands in space, and nobody anymore understands what underlies the results; the information is hidden. Also, any optimization and/or comparison of actions, effects and relationships is done through Mela-simulations - there is no attempt to *understand and communicate* intuitively whether, how and to which extent management can help achieving climate policy goals (i.e. good inventory results). And: is managing for good inventory results climate and forest-positive?

2.3 Net CO₂ balance of residues (Term III)

Term III in eq. 3 represents the annual change in residue carbon (*C*) pool per unit area (in CO₂ equivalents). It is computed using mass-conserving dynamic model YASSO07 (Tuomi et al., 2009), which describes organic matter decomposition as coupled first-order decay equations (?) that account for the cascade of organic matter from rapidly decomposing to more persistent forms and ultimately to slowly decomposing humus. At each timestep, each *C* pool decomposes at rate that is linearly proportional to the pool size and environmental modifier (representing the effect of temperature and moisture). The decomposing C is then either transferred to other pools, or respired to the atmosphere as CO₂. Alm et al. (2023) use YASSO07 with Scandinavian parameter set and apply 50-year spinup with residue litter inputs equal to 1990 level to initialize the carbon pools. The dynamics of residue *C* pools is then computed annually using annual residue litter inputs, and environmental modifier that is based on 30-year running average annual air temperature (T_a) and precipitation sum (P_{cum}).

The net residue CO₂ sink/source (i.e. term III) thus equals the total change in residue *C* pools

$$F_r(t) = (I_{AGR} + I_{BGR}) - (D_{AGR} + D_{BGR}) = \frac{\partial M_{residue}(t)}{\partial t} dt, \quad (10)$$

where t denotes time (year) and dt is the annual timestep. The eq. 10 is mass-conserving and dynamic, which has important implications. First, the residue net CO₂ sink/source at a given year t depends on 'history' of litter inputs, and *current conditions* (litter input, climate) at each year of interest. Fig. 9 (middle row) in Alm et al. (2023) suggests that the initial state of residue *C* pool at 1990 have been close to steady-state, and the 30-year climatic trends (ca. +1.3-1.4°C in T_a and xxx mma-1 in P_a from 1990 to 2020) have only a minor effect on decomposition rates and thus on $F_{residue}$. Second, as harvests and associated residue litter input have increased during the 1990-2020 period, and peatland forest harvesting has had a *positive effect* on soil CO₂ balance. There has been net accumulation (i.e. sink) of residue *C* both in Southern and Northern Finland; however note strong inter-annual variability in the sink strength which is determined nearly completely by changes in annual residue input.

Conclusion: harvesting / not collecting cutting residues increases residue litter input, which is beneficial for soil CO₂ balance: the residue C pool act as net sink. And climatic trends have negligible impact on residue CO₂ balance (but see how similar residues from living trees are decomposed as part of Term II).

3 Critical remarks

3.1 Litter influxes

The estimates of above-ground biomass of peatland forests are based on standardized NFI measurements and *should* be the most credible part of the GHG inventory. Likewise, all litter inputs are now derived from the NFI stand attributes, using biomass expansion factors (BECF's) on mean stem volume V , and harvest statistics. In terms of estimating above-ground biomass and annual litter production as a whole, the new peatland GHG inventory method is consistent with that used on mineral soils (?). However, note that the relationship between annual tree litter flux and mean BA (Fig. 2 rightmost panel) is generally decreasing with time, most likely due to non-linearity of foliage biomass with stem volume (and mean BA). This means that for a given increase in BA (e.g. by delayed harvests or improved growth rates), F_L increases the less the higher the average BA.

More importantly, the decreasing trend in $\beta_{j,k}$ is not smooth at all site types, as one would expect for large inventory regions with slow changes in BA and stem volume distributions. There seems thus to be some inconsistencies either or both in i) how fertility type-specific mean stem volumes are computed from NFI plot-level data for each NFI, and ii) in BECF's used to convert volume to compartmental biomasses. The Appendix e6 of NIR inventory reporting for Finland (?) states that: *"Biomass conversion and expansion factors, BCEFS were computed separately for each NFI as a ratio of appropriately weighted mean biomass and mean stem volume estimated over the NFI sample trees belonging to the respective strata (SL note: for different region and site type separately)," ... "Each estimate biomass estimate was allocated to the appropriately weighted mean of the measurement dates. The linear trend estimated based on the difference between NFI9 and NFI8 was applied to extrapolate to the years preceding the mean measurement date of NFI8. The trend in total biomass has been increasing since 1990."*

The applied methodology can explain the level-jumps in litter flux / BA -ratio (Fig. A3), particularly clear for pine (Fig. A1 & A2). The use of *different BECF's* for different NFI's and creates inconsistencies in tree biomass estimates. Further, as tree litter production is linearly proportional to living biomass, and reduction of litter fall has proportional impact on soil CO₂ balance, on estimated peatland GHG balance. This can be seen e.g. in Fig.

NIR-report: *"The stem volume of the drain was converted to whole tree biomass and biomass of the tree compartments using expansion factors, which were computed from the permanent sample plot data. Employed permanent sample plots were established in the NFI9 (1996 to 2003) and remeasured in the NFI10 (2004 to 2008). Separate expansion factors were computed for the fellings and for the unrecovered natural losses as the ratios of biomass stocks and stem volume stocks estimated from the NFI9 measurements from trees harvested or dead between the inventories. The same factors were applied for the whole time series."*

3.2 Soil CO₂ balance

Eq. 6 has an important property that compromise its validity, and makes estimates of peat soil CO₂ balance subject to arbitrary decisions: The CO₂ emissions ($F_{dec,j}$) [g CO₂ m⁻² a⁻¹] from decomposition of peat and litter from living plants (Term II, eq. 7) does not depend *explicitly* on current year or historical litter influxes. This is because litter and peat decomposes and emits CO₂ at a rate that is independent from the litter input fluxes providing the decomposable material. Thus, any uncertainty

in F_L (see above) will have proportional impact on $CO_{2,Net}$, as there is no proportionality between F_L and F_{dec} through
150 mass-balance. It is also questionable how similar litter from living plants can be treated differently to the residue litter.

The temperature sensitivity $\alpha_2=242.8$ [g CO₂ m⁻² a⁻¹ degC⁻¹] is extremely strong, and corresponds to Q_{10} values ranging from... see Fig. 4.

Study data & methodology in Ojanen et al. -papers. Accounting litter decomposition is fishy...

155 Replace current decomposition model by Ojanen WTD - T -dependency ("same data, different interpretation"). Simulate WTD with Susi; analyze whether there have been significant trends in summer WTD and thus oxic layer depth. What is the effect on decomposition; is the 'climatic trend' i.e. temperature effect as strong? Move then towards more feasible SOM-models.

4 Conclusions

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Code availability. TEXT

160 *Data availability.* TEXT

Code and data availability. TEXT

Sample availability. TEXT

Video supplement. TEXT

Appendix A: Suppl. Figures

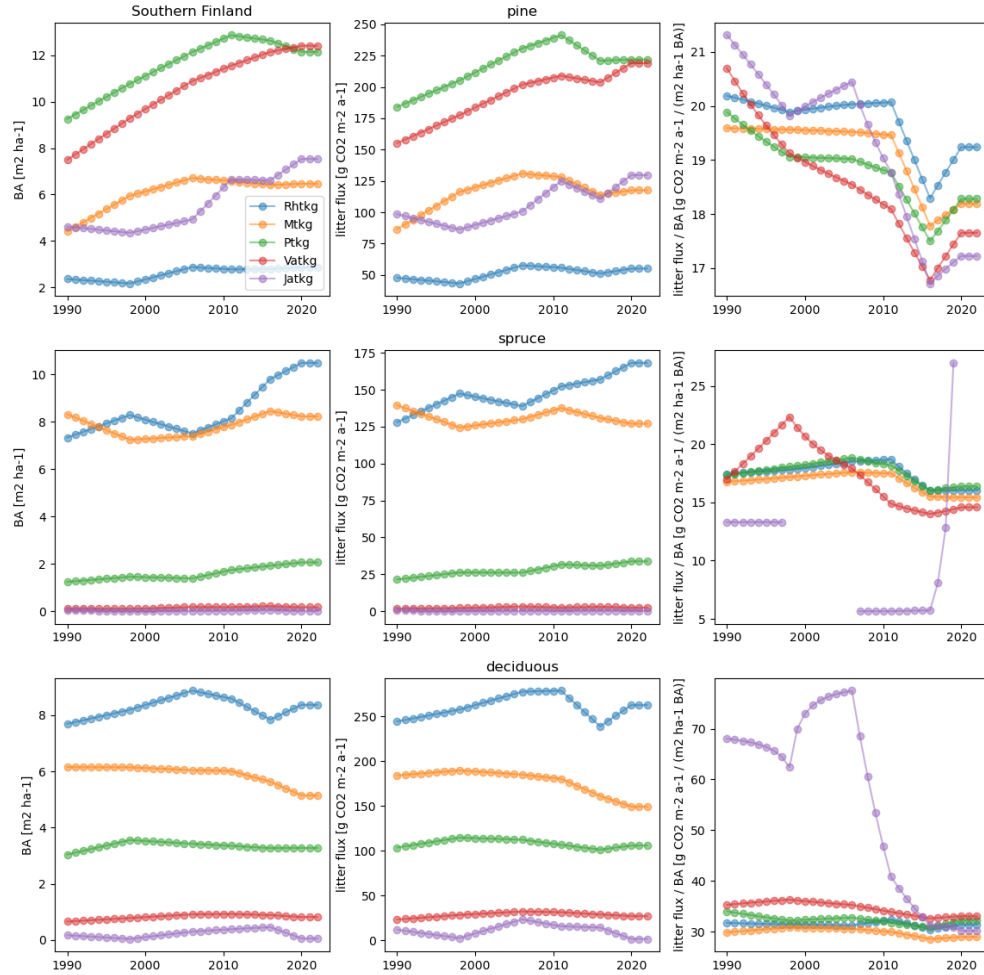


Figure A1. Basal areas (BA), annual litter input flux from living trees (excl. fineroots), and the ratio of tree litter flux and BA for each species in Southern Finland. Data from Alm et al. (2023) Zenodo supplementary.

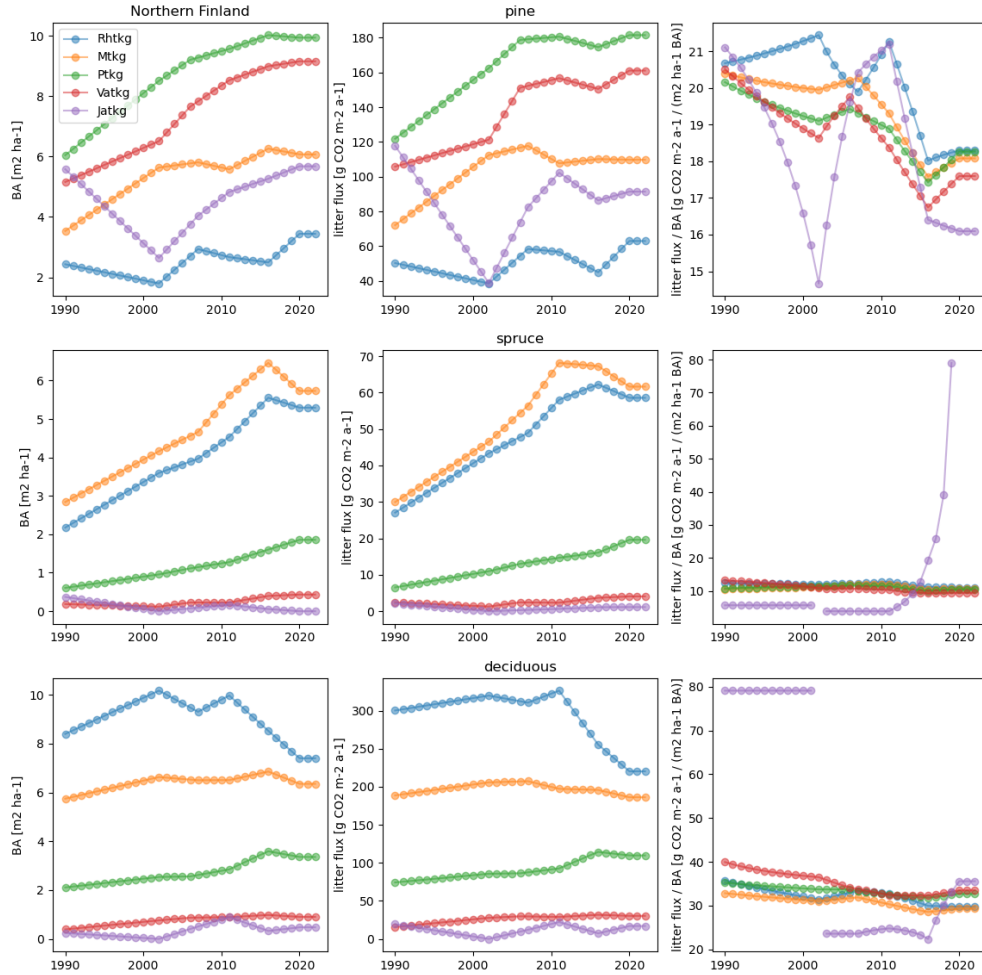


Figure A2. Basal areas (BA), annual litter input flux from living trees (excl. fineroots), and the ratio of tree litter flux and BA for each species in Northern Finland. Data from Alm et al. (2023) Zenodo supplementary.

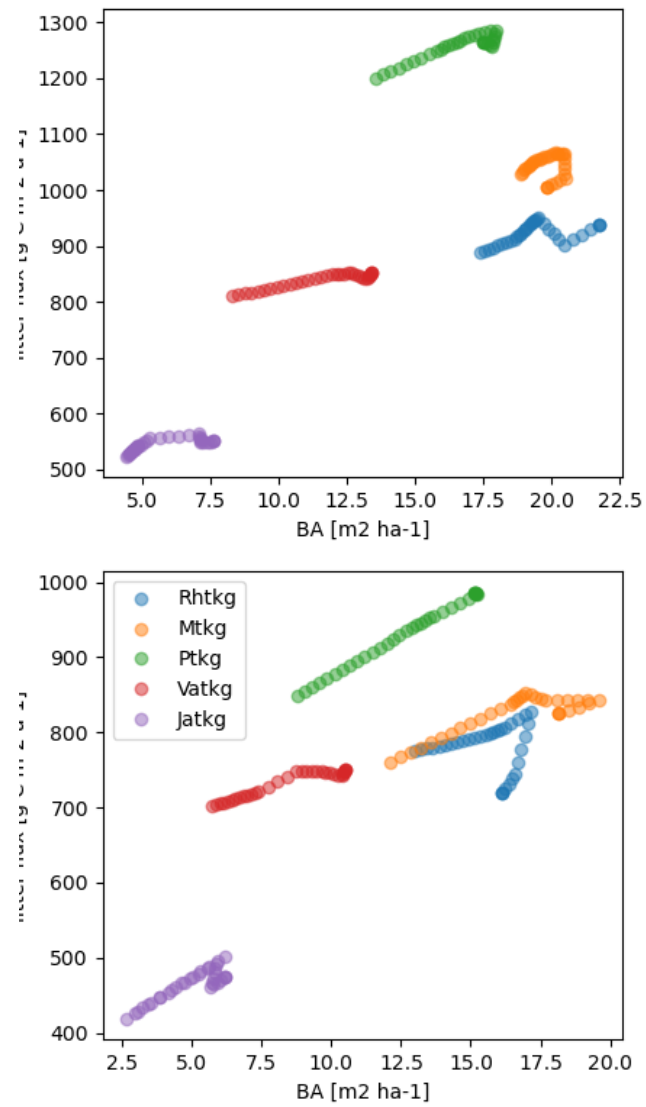


Figure A3. Total annual total litter influx (excl. residues) vs. mean basal area (BA) at each site type and region. Data from Alm et al. (2023) Zenodo supplementary.

Author contributions. TEXT

Competing interests. TEXT

Disclaimer. TEXT

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