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Perspective Article

Critical biomass harvesting indicator for whole-tree extraction does not reflect the sensitivity of Swedish forest soils

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ABSTRACT

There is a growing societal demand to increase the use of forest biomass for substitution of fossil fuels. The production of this biomass must be sustainable and an indicator for critical biomass harvesting (CBH) has been suggested in order to sustain forest soil fertility and mitigate soil acidification at whole-tree harvesting. The CBH indicator is based on an acidity mass balance approach in line with the critical load of acid deposition (CL) concept. Countries like Sweden, the Netherlands and the state of Quebec, Canada apply such mass balance approaches for developing forest biomass harvesting guidelines. The implementation of this type of policy instrument may restrict the use of harvest residues for bioenergy and thereby the substitution of fossil fuels. It may as well affect the forestry sector revenue negatively. To maintain credibility for enforced limitations, it is important that the risk assessment and suggested policy implications are based on solid scientific methods and assumptions. The mass balance approach have been criticized for being too uncertain and not sufficiently validated for being used to guide ecosystem management. In this paper we use published Swedish data on soils, acid deposition, forest production and information from international scientific literature to critically examine the CBH indicator. We conclude that the CBH indicator 1) does not account for all relevant processes 2) it exaggerates the sensitivity and correlates poorly to actual forest soil acid-base status and edaphic conditions and 3) data availability does not allow the indicator to be calculated at a high enough spatial resolution for advice on management for forest owners. The concerns for the mass-balance approach and CBH indicator are discussed in an international perspective.

1. Introduction

The "Critical load" concept (Nilsson and Grennfelt, 1988) is used for policy negotiations worldwide within the Convention on Long-range Transboundary Air Pollution (CLRTAP) for diminishing the emissions of sulphur and nitrogen (Grennfelt et al., 2020). The convention and CL concept have had a tremendous impact on society and have resulted in large emission reductions, diminished exceedance of CL and increased acid neutralizing capacity (ANC) in many North American and European forest streams (Clark et al., 2018; Forsius et al., 2021). A similar approach has been suggested for forest biomass harvesting (Akselsson and Belyazid, 2018) in order to reduce the acidifying effect of forestry. The indicator is based on acidity mass balances and a "Critical biomass harvesting" (CBH) level, which corresponds to the harvesting level when acid neutralizing capacity (ANC) in soil solution equals zero (Akselsson and Belyazid, 2018, see below). The critical biomass harvesting level (is intended to be used for identification of sensitive and less sensitive areas for whole-tree harvesting.

There is a growing societal demand to increase the use of forest biomass for substitution of fossil fuels in order to reduce the CO_2 climate impact (European Commission, 2016). The production of this biomass must be sustainable (Gonçalves et al., 2021; Camia et al., 2021), which is a complex concept (UN, 2015). Besides socio-economic issues, sustainability covers a broad range of biodiversity and ecosystem services (Ranius et al., 2018; Forsius et al., 2016; de Jong et al., 2017; Titus et al., 2021). Soil fertility and potential acidification based on mass-balances have been used as indicators for sustainable forest production and biomass extraction (van Breemen et al., 1983; Ranger and Turpault, 1999; Thiffault et al., 2011; Achat et al., 2015; Nilsson, 1988) as well as for improving biomass harvesting guidelines (de Vries et al., 2021; Titus et al., 2021; MFFP, 2020). However, these nutrient mass balances have been criticized for being too uncertain and insufficiently validated for

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being used to guide ecosystem management (Paré and Thiffault, 2016)

In a recent review, Titus et al. (2021) showed that a number of jurisdictions in North America and Europe have adopted forest biomass harvesting guidelines for sites and soils prone to nutrient depletion and acidification. The descriptors relate to nutrient poor sites, reduced nutrient inputs and soil acidity defined by physical properties, vegetation or soil classification and a few countries/states apply acidity mass-balances. The Swedish Environmental Protection Agency (Swedish EPA), the responsible authority for the national environmental objective “Natural Acidification Only”, has adopted the CBH indicator (Swedish EPA, 2019). The Ministère des Forêts, de la Faune et des Parcs in Quebec, Canada, also uses the CBH concept in the guide to regulate the sustainable development of forests, aiming at avoiding long-term losses in soil productivity in certain ecological sub-regions, ecological types and potential vegetation types (MFFP, 2020). A similar guideline approach, restricted to vegetation type on sandy soils, is suggested for forestry in the Netherlands (de Vries et al., 2021).

A clarification to the Swedish acidification objective states that “Land use’s contribution to acidification of soil and water is counteracted by adapting forestry to the acidification sensitivity of the site” (Swedish EPA, 2021). The Swedish Forest Agency, supervisory authority for sustainable forest production according to the Forestry Act, cope with this clarification by recommending wood ash recycling to forest stands when harvesting of tops and branches (whole-tree harvesting, WTH) exceeds a dry weight (dw) production of 0.5 ton dw ash/ha during a rotation period (Swedish Forest Agency, 2019). Due to the historically high acid deposition in the southern and southwestern parts of Sweden, ash return is always recommended without reference to harvest level.

In a recent article, the CBH concept was complemented with a risk classification of WTH (Akselsson et al., 2021). The estimated CBH_{Exc} (loss of buffering capacity) was compared with ANC in soil solution (present acidification status) at 26 forested Swedish sites. Thereafter, an acidification risk classification was performed based on the relation between CBH_{Exc} and soil solution ANC. Based on this risk assessment, policy implications were discussed affecting the potential for WTH and the needs for compensation measures such as ash recycling or a complete ban on whole-tree harvesting.

The acceptance of this type of policy instrument by authorities in governance may have important implications for the bioenergy production. It may restrict the use of harvest residues and thereby the substitution of fossil fuels as well as affect the forest owner’s economical outcome by diminished harvests and/or demands for costly countermeasures. Hence, it is important that the risk assessment and suggested policy implications are based on solid scientific methods and assumptions (Titus et al., 2021), which have been questioned (Kimmins, 1976; Paré and Thiffault, 2016). We are concerned over the use of indicators such as the CBH indicator for development of forest management policies for three reasons:

- The indicator does not account for all relevant processes and recent data challenges basic concepts used in the indicator
- The indicator exaggerates the sensitivity and correlates poorly to actual forest soil acid-base status and edaphic conditions
- Data availability does not allow the indicator to be calculated at a high enough spatial resolution for advice on management

Here we critically examine the CBH indicator based on published Swedish data on soils, acid deposition, forest production and make comparisons with the results from a recently published scientific article on acidity loads to Swedish forest soils during the period 1955–2010 (Karltun et al. 2021). The relevance of the concept is discussed in an international perspective and primarily from a base cation and acidification perspective.

2. Methods

2.1. CBH_{Exc} and acidification risk classification of WTH

The methods for estimating critical biomass harvesting (Akselsson and Belyazid, 2018) and the following risk classification (Akselsson et al., 2021) are briefly described here. For a more detailed description, see the original papers.

The critical biomass harvesting level (CBH) is based on the Simple Mass Balance (SMB) critical load equation (CLRTAP, 2017) rearranged so that the corresponding critical extraction of base cations is calculated instead of critical load of acid deposition (CL). It is defined as the point when the base cation removal (Eq. (1)) from harvesting (BC_{CBH}, Eq. (2)) is balanced by the other variables in the SMB. This also defines the maximum biomass extraction level that does not lead to an acid neutralizing capacity (ANC, Eq. (3)) below zero in soil solution leaving the root zone (50 cm soil depth) and therefore does not cause export of acidity to surface waters (Akselsson and Belyazid, 2018).

In principle, BC_{CBH} (Eq. (2)) is calculated from the amounts of base cations (BC) in harvest biomass (BC_{harv}, Eq. (1)) compared with other sources of alkalinity (positive terms) and acidity (negative terms) to the soil solution, respectively. The annual amounts are expressed as charge per area (eq ha^{-1} yr^{-1}).

$$BC_{harv} = BC_{harv,Ca2+} + BC_{harv,Mg2+} + BC_{harv,K+} + BC_{harv,Na+} \quad (1)$$

$$BC_{CBH} = BC_{weath} + BC_{dep} + NH_4\text{-}N_{leach} - S_{dep} - Cl_{dep} - NO_3\text{-}N_{leach} \quad (2)$$

where BC = sum of Ca^{2+}, Mg^{2+}, Na^+ and K^+, eath = weathering, dep = deposition, harv = net losses at harvesting, leach = leaching

Alkalinity leaching is per definition zero and therefore omitted from Eq. (2)

Exceedance of the critical biomass harvest (CBH_{Exc}) occurs when $BC_{harv} > BC_{CBH}$.

Here we use data calculated by the Swedish Forest Swedish Forest Agency (2021) on the proportion of Norway spruce (*Picea abies*, (L.) H. Karst) stands where CBH_{Exc} is greater than zero after WTH and without ash return (Table 1). The calculations are made according to Akselsson and Belyazid (2018) on data from the Swedish National Forest Inventory (NFI). The results are aggregated at county level (Fig. 1).

The risk classification study (Akselsson et al., 2021) includes 26 sites distributed all over Sweden, but most of them (21 sites) are located south of the W and X counties in Fig. 1. Harvested biomass was calculated from site productivity and an estimated optimal stand growth reduced by 20% to imitate real conditions. Standard methods were used to separate the biomass between stems, branches and needles, assuming 100% harvest of stems, 60% of branches and 75% of the needles at WTH. The harvested amounts of BC derived from multiplying biomass with national average values on BC concentrations for each tree species and fraction, summed to a total BC_{harv}. Weathering rates of BC were estimated with the steady state model PROFILE and the mineralogy in different soil horizons were estimated from total element content and the A2M program (Posch & Kurz, 2007). Akselsson et al. (2021) complemented the CBH_{Exc} estimates with a WTH acidification risk classification (*high, medium, low*) based on the relation between CBH_{Exc} and ANC in soil solution (Eq. (3)). At ANC < 0 and $CBH_{Exc} > 0$, the risk for acidification related to WTH was defined *high* (Risk Class 1) while the opposite (*low*) was true if ANC > 0 and $CBH_{Exc} < 0$ (Risk Class 3). If either ANC < 0 or $CBH_{Exc} > 0$, a *medium* acidification risk (Risk Class 2) related to WTH was anticipated.

$$\text{ANC}\ (\text{meq l}^{-1}) = [Ca^{2+}] + [Mg^{2+}] + [K^{+}] + [Na^{+}] + [NH_4^{+}] - [SO_4^{2-}] - [Cl^{-}] - [NO_3^{-}] \quad (3)$$

Table 1
At county level, the proportion of Norway spruce stands exceeding the critical biomass harvesting ($CBH_{Exc} > 0$) at WTH and no ash return, the proportion of acidified soils, the median and minimum pools of exchangeable base cations in soils (1 M ammonium acetate, pH = 7, humus and 0–50 cm mineral soils) and the base cation pool in standing tree biomass. The counties are ordered from north to south and when multiple counties are located at similar latitude the counties are ordered from west to east (cf. Fig. 1).

County	Code	$CBH_{Exc} > 0$ (%)[1]	Acidified soils (%)[2]	BC $soils_{Median}$ ($kmol_c$/ha)[2]	BC $soils_{Min}$ ($kmol_c$/ha)[2]	BC $Biomass_{Mean}$ ($kmol_c$/ha)[2]
Norrbotten	BD	4%	15%	17.1	2.4	7.4
Västerbotten	AC	7%	19%	17.6	1.7	9.8
Jämtland	Z	1%	23%	26.3	3.4	11.0
Västernorrland	Y	3%	16%	24.5	4.5	13.9
Dalarna	W	13%	44%	14.6	2.7	10.5
Gävleborg	X	15%	20%	20.8	3.4	12.2
Värmland	S	13%	41%	17.1	2.5	14.2
Örebro	T	33%	40%	19.1	2.9	14.9
Västmanland	U	2%	21%	52.1	7.9	13.6
Uppsala	C	34%	17%	237.1	17.3	14.9
Stockholm	AB	18%	13%	79.6	15.1	14.9
Södermanland	D	49%	20%	57.4	6.4	14.9
V. Götaland	O	19%	54%	22.2	3.1	16.7
Jönköping	F	47%	51%	20.1	3.4	16.2
Östergötland	E	62%	34%	30.1	5.9	14.6
Halland	N	21%	76%	16.4	7.0	17.9
Kronoberg	G	13%	57%	18.2	6.0	14.7
Kalmar	H	33%	38%	32.2	3.6	14.9
Blekinge	K	48%	47%	18.7	0	15.6
Gotland	I	0%	0%	483.4	34.1	9.1
Skåne	M	35%	66%	23.6	5.2	14.8

[1] Data from the Swedish forest Agency (2021).
[2] Data from Karltun et al. (2021).

Based on this risk assessment, policy implications were discussed and Akselsson et al. (2021) suggest that:

- "…whole-tree harvesting at sites belonging to Risk Class 1 is not compatible with the Swedish environmental objective about acidification, even if the removal of base cations is compensated for by wood ash recycling".
- "We suggest that whole-tree harvesting at sites belonging to Risk Class 2 should be accompanied with wood-ash recycling".
- "In Risk Class 3, … the risk of negative effects of whole-tree harvesting on the acidification status is small, and that wood-ash recycling is not necessary at those sites".

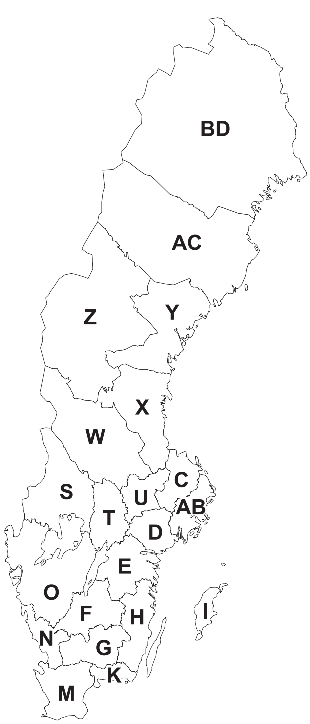

Fig. 1. Swedish counties marked with codes. Full names are found in Table 1.

2.2. Acidity loads, BC sources and acidification of Swedish forest soils

Recently, Karltun et al. (2021) estimated the input of acidity to Swedish forest soils from forestry and atmospheric deposition during the period 1955–2010. At county level (Fig. 1), the acidity load was compared with the stocks of exchangeable base cations and the proportion of acidified soils (see below for definition). Data from the Swedish NFI were used to estimate the stocks of standing biomass and the harvests of stem biomass during the period 1955–2010. Extraction of harvest residuals were calculated only for the period 1999–2010 since the extraction of harvest residues was negligible before that. Based on Swedish and Finnish data, the stocks of both cations (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}) and anions ($H_2PO_4^{-}$, SO_4^{2-}, Cl^{-}) were estimated for different tree species and tree parts. On molar basis, the annual net production of acidity was calculated as the difference between cations and anions, in the following termed net-BC uptake (Net-BC_{upt}, Eq. (4)), in standing biomass and biomass harvest. For a more detailed description of the methods, see the original paper and Iwald et al. (2013).

(Eq. (4))

$$\text{Net} - BC_{upt} = BC_{harv,Ca2+} + BC_{harv,Mg2+} + BC_{harv,K+} + BC_{harv,Na+} - - (BC_{harv,H2PO4} + BC_{harv,S242-} + BC_{harv,Cl-}) \quad (4)$$

The Net-BC_{upt} method (Karltun et al., 2021) deviates from the BC_{harv} method used by Akselsson and Belyazid (2018) and Akselsson et al. (2021), who did not take into account the alkalization effect of the anion uptake by trees (cf. Eq. (2)), nor the acidity loads related to increased standing biomass. The latter is currently at the same level as the biomass harvest in Sweden (Karltun et al., 2021).

Data from the Swedish Forest Soil Inventory (SFSI), collected during the period 2003–2012 from ca 3600 forest soil plots excluding those located on organic soils, were used for estimating the stocks of exchangeable base cations (1 M ammonium acetate, pH = 7) in the humus layer and 0–50 cm mineral soil, corresponding to an assumed root depth. As indicator of soil acidification the proportion of acidified soils were estimated from pH in the B-horizon ($pH_{H2O} < 4.5$) or the C-horizon ($pH_{H2O} < 4.75$), which is a method suggested by the Swedish Forest Agency (Gustafsson et al., 2001). The degree of acidification in a Swedish forest soil reflects the weathering rates of minerals in the parent material and the accumulated effect of acidifying processes since the last glaciation. Acid deposition and biomass accumulation and export are major processes for acid input. Soils that currently are acidified according to the definition above are either inherently more sensitive to acidification or has been subjected to a higher acid input than the less acidified soils. We therefore assume that the proportion of acidified soils should reflect if a geographic area is sensitive to maintained or increased export of base cations. The results were aggregated at county level and thereby geographically comparable with the Swedish NFI data on CBH_{Exc} (Table 1).

3. Results and discussion

3.1. The indicator does not account for all relevant processes

The estimated proportion of Norway spruce stands at county level exceeding the critical biomass harvesting at WTH and without ash return varies between 1 and 62% (Swedish Forest Swedish Forest Agency, 2021, Table 1), with the largest shares (>30%) in southeast Sweden (county codes C, T, D, E, F, K, Fig. 1). The exceedances are low (1–7%) in northern Sweden (BD, AC, Z, Y) and in the south central county Västmanland (U), while no exceedance occurs on the calcareous island of Gotland (I). The remaining counties located on the Swedish west coast (N, O) and along a band across the southcentral parts of the country (S, W, X) show CBH_{Exc} in the range 13–20% (Table 1).

According to the CL concept, the acidity load from forestry is defined from net uptake of BC in biomass as “the net uptake by vegetation that is needed for long-term average growth” (CLRTAP, 2017). Hence, the acidity load equals the sum of net BC uptake in forest biomass, where the alkalization effect of anion assimilation reduces the acidity load from the gross BC uptake. The CBH concept (Eq. (2)) simplifies this by only calculating the acidity load from BC harvesting without taking into account acid-base effects related to changes in anion uptake.

Table 2
Anion uptake of totally assimilated ions (%, equivalent basis) in different tree parts separated on the most common Swedish tree species. Data from Iwald et al. (2013).

Tree species	Tree part	Anion uptake fraction of totally assimilated ions at equivalent basis
Scots pine (*Picea abies*)	stemwood	17%
	bark	16%
	branch	14%
	needle	23%
Norway spruce	stemwood	8%
(*Pinus sylvestris*)	bark	7%
	branch	14%
	needle	15%
Birch	stemwood	7%
(*Betula* spp.)	bark	8%
	branch	14%
	leaf	17%

Based primarily on Swedish and Finnish data, Iwald et al. (2013) estimated the anion uptake ($H_2PO_4^-$, SO_4^{2-}, Cl^-) in different tissues of the three most common tree species (Table 2), corresponding to 95% of the Swedish timber volume (SLU, 2017). The excess biomass extraction at WTH compared with conventional stem-only harvest (SOH) is the removal of a large fraction of tops, branches and needles/leaves.

Hence, the overlooked anion uptake is a quantitatively important obstacle since it creates a non-existing acidity load due to charge imbalance (Eq. 4). Based on the Iwald et al. (2013) anion uptake data (Table 2), the CBH concept overestimates the acidification effects of WTH with up to 29–37% (sum of branches and needles/leaves) by not using Net-BC_{upt}. The lowest percentage is relevant for the CBH_{Exc} indicator for Norway spruce used by the Swedish Forest Agency (2021). Applying Net-BC_{upt} would most certainly reduce the number of sites with $CBH_{Exc} > 0$ and thereby the number of sites in Risk Class 1 and 2.

3.2. The indicator correlates poorly to actual forest soil acid-base status and edaphic conditions

An often overseen fact is that the acidity load is not related to the harvest occasion, but throughout the period of forest growth beforehand the harvest. That means that the CBH mass-balance WTH acidity load reflects the forest growth between ca 65 to >100 years in southern and northern Sweden, respectively. The biological acidification reaches its maximum, accumulated effect just before harvest, whereafter it becomes permanented in the context of BC removal and the potential BC availability and soil acidity. Therefore, we hypothesize that the CBH_{Exc} indicator, based on the forest status 2014–2016 (Swedish Forest Swedish Forest Agency, 2021), should be reflected in the Swedish FSI data from 2003 to 2012, identifying the counties with the most vulnerable soils to WTH i.e. acidified or low BC pool soils.

Excluding the calcareous island of Gotland (I), the proportion of acidified soils (Karltun et al., 2021) varies in the range 15–76%, with the highest shares (>40%, Table 1) in the southwest and southcentral parts of Sweden (K, M, N, O, G, F, S, T, W, Fig. 1). In the counties with forest soils influenced by $CaCO_3$ or high clay content (AB, C, D, U, I), the pools of exchangeable base cations in soils (humus and 0–50 cm mineral soils) are high compared with the others. In the former, the median values (BC $soils_{Median}$) are 52–237 $kmol_c$/ha, while this range is 15–32 $kmol_c$/ha in the more BC poor counties (Karltun et al., 2021). The minimum pool of exchangeable base cations in each county (BC $soils_{Min}$, Table 1) show a somewhat similar geographical pattern except for that some of the southern (M, N) and southeastern counties (G, E) tangent the lowest value 6 $kmol_c$/ha at the BC rich sites. In the county of Blekinge (K), the minimum exchangeable BC pool was extremely low and close to zero. Except for the BC rich counties, the base cation pool in standing tree biomass holds 42–109% of the amounts of salt extractable BC in soils (Table 1). This range is 2–26% in the BC rich counties.

Based on data in Table 1, Fig. 2 shows that there are no significant linear relations ($p > 0.05$) between CBH_{Exc} and the share of acidified soils or the soil BC pools neither expressed as minimum or median values for the counties. The counties with the highest CBH_{Exc} values (20–60% of the soil sampling sites) and identified as most vulnerable to WTH, did not show any significant relation with these variables. However, Karltun et al. (2021) showed at county level that the proportion of acidified soils in Sweden reflects the geographical gradient in acid input from forestry and atmospheric deposition, but they concluded that edaphic properties such as mineralogy and soil texture are of considerable importance. The only statistically significant relation is between CBH_{Exc} and the BC pools in standing biomass. This is expected since this type of nutrient budget indicator tends to classify productive sites as more sensitive than low productive ones (Paré et al., 2021) also mentioned by Akselsson et al. (2021).

Based on data primarily representing the southern part of Sweden with higher acid deposition and forest growth, Akselsson et al. (2021) suggested a complement of the acidification risk classification with ANC

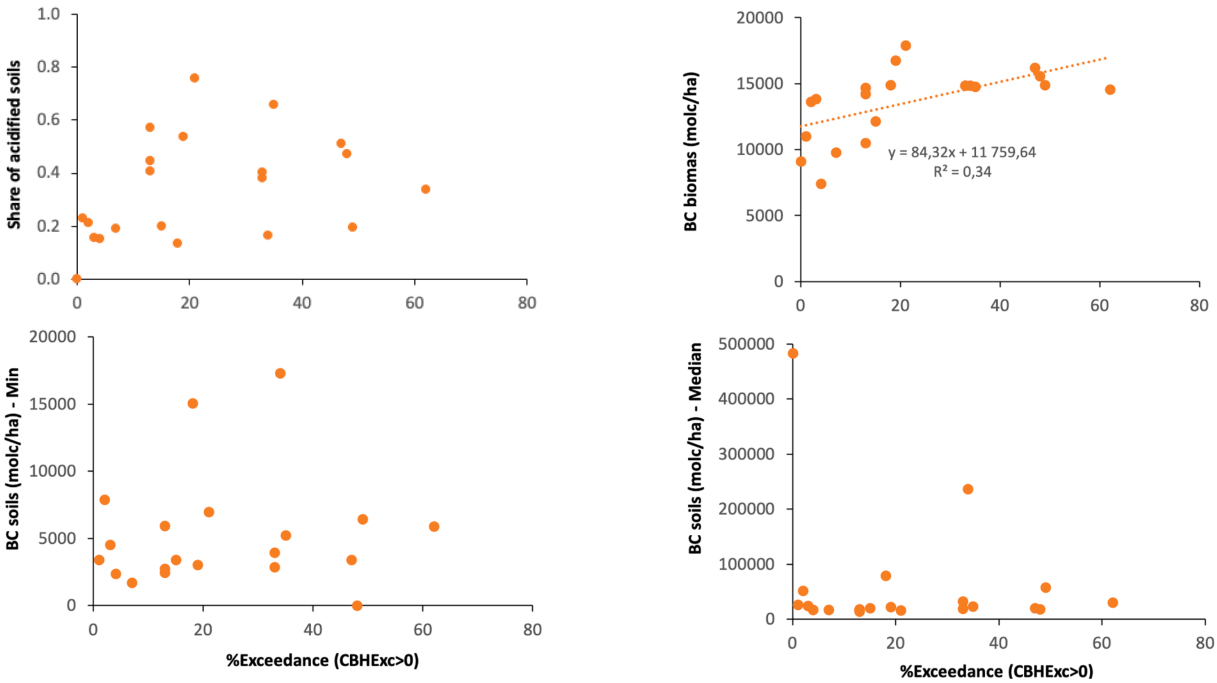

Fig. 2. Relations at county level between the share of Norway spruce forests exceeding critical biomass harvest at whole-tree harvest ($CBH_{Exc} > 0$ (%)) and the share of acidified soils (%, upper left), the amounts of BC in tree biomass (BC biomass, mol_c/ha, upper right), the minimum amounts of exchangeable BC in soils (BC soils (mol_c/ha – Min, lower left, excluding the non-acidified, calcareous island Gotland (I)) and the median amounts of exchangeable BC in soils (BC soils (mol_c/ha – Median, lower right). The statistically significant ($p < 0.01$) linear relation between $CBH_{Exc} > 0$ and BC biomass is shown by the regression line and equation, n = 21.

> 0 in soil solution (Eq. 3). However, processes not related to biomass production and harvest *per se* may induce ANC < 0, reducing the value of ANC as forestry acidification indicator. Examples on such processes are ion exchange caused by sea salt deposition (Hindar, 2005) or proton production related to oxidation of reduced sulfur, nitrogen and chlorine compounds present in e.g. organic matter (van Breemen et al., 1983; Svensson et al., 2021). Additionally, stand information on soil solution chemistry is in most cases missing.

BC mass-balance data in combination with other types of site specific information are applied elsewhere. In New Zealand, Garrett et al. (2021) used nutrient mass-balance model estimates for multiple rotations in combination with site information on the initial state and nutrient capitals as a tool for sustainable precision nutrient management, improved productivity and to prevent N leaching. For guidelines in the Netherlands, de Vries et al. (2021) suggest tree-species, sandy soil type and region as complementing indicators for adverse effects on soil fertility.

3.3. Recent data challenges basic concepts used in the indicator

In a recent review, Paré and Thiffault (2016) discuss knowledge gaps and uncertainties associated with nutrient mass-balances. They conclude that the approach may be appropriate for intensively managed short-rotation plantations, but inadequate for long-rotation systems in boreal and temperate forests due to complexity, large uncertainties in several flux estimates, lack of feed-back mechanisms and no validation. We agree on these statements and discuss them in a Swedish context below.

Reliable BC weathering rates estimates are crucial for assessing the sustainability of forest biomass harvesting (Eq. 2). Based on silicate mineral Swedish forest soils, the BC weathering rates estimates are highly dependent on estimation method, but are generally in fairly good agreement regionally. At single-site level, however, the uncertainties are large (Akselsson et al., 2019; Casetou-Gustafson et al., 2020; Klaminder et al., 2011), confirming international results (Futter et al., 2012). As an example, Simonsson et al. (2015) showed that the confidence intervals for the BC weathering rates exceeded the estimated mean values with>100% based on replicated BC budgets (n = 4) for a Norway spruce (*Picea abies* (L.) Karst.) stand in southern Sweden.

Besides weathering and exchangeable, salt extractable pools there are "hidden" BC stocks probably reflecting secondary formed, non-crystalline minerals and organically bound forms (Bel et al., 2020; Rosenstock et al., 2019; Prietzel et al., 2021). Extraction experiments and isotopic dilution studies have shown that forest soils host potentially available BC fractions not related to minerals or the cation exchange complex (CEC). Based on mineral soils from the Swedish integrated monitoring sites (Löfgren et al., 2011), isotopic dilution studies by Bel et al. (2020) indicate that the Ca-pools (E_{Ca}) may be 2–15 times as large as the Ca pools determined with traditional salt extraction ($Exch_{Ca}$, Table 3). For Mg and K, these pools are smaller and within 1.5–2.1 and 1.4–2.4 times the salt extractable fraction, respectively (Table 3).

The BC release rates from these "hidden" BC pools are not accounted for in the BC mass-balance (Eq. (2)) and a number of studies indicate a missing BC source (Casetou-Gustafson et al., 2020; Zetterberg et al., 2016; van der Heijden et al., 2014; van der Heijden et al., 2018; Erlandsson Lampa et al., 2019; Legout et al., 2020; Rosenstock et al., 2019). Isotopic dilution studies by Bel et al. (2020) indicate e.g. 2–15 times larger Ca pools in the mineral soils compared with the traditional salt extraction method at the Swedish integrated monitoring sites (Table 3). From the mineral soils at Kindla SE15, relatively weak acid extractions (0.2 M HCl) released considerably more base cations than

Table 3
Relations between BC-pools determined with traditional salt extraction ($Exch_{Me}$) respective isotopic dilution (E_{Me}) at the Swedish IM sites. Data from Bel et al. (2020).

Site	$E_{Ca}/Exch_{Ca}$	$E_{Mg}/Exch_{Mg}$	$E_K/Exch_K$
Aneboda SE14	7.2	1.9	2.0
Gammtratten SE16	15.4	2.1	2.4
Gårdsjön SE04	2.1	1.5	2.2
Kindla SE15	13.0	1.7	1.4

found in the salt-extractable pool. Depending on hydrologic location along the studied hillslope, the extracted Ca^{2+} amounts were equivalent to the supply needed for 5–10 forest harvest rotations of 65 years (Rosenstock et al., 2019).

A third uncertainty in the CBH mass-balance is the uptake of anions and cations in biomass (Eq. (2) and (4)). Model predictions of WTH effects on soils and water points e.g. at the needs for site-specific Ca^{2+} concentrations in tree biomass and the potential for adaptive Ca^{2+} uptake by vegetation as well as biological feed-back mechanisms that can increase the Ca^{2+} availability (Zetterberg et al., 2014). As an example of the latter, model predictions based on data from four Swedish experimental sites indicate that input of Ca^{2+} litter production in the following forest stand may offset the WTH induced Ca^{2+} decline (Hyvönen et al., 2012). Based on primarily French data, Legout et al. (2020) show that litterfall and plant internal cycling may supply plant nutrition and replenish the soil reservoir at sites with low geochemical input (e.g. weathering, atmospheric deposition).

As already mentioned, the soil nutrient and acidification effects of forestry are largest just before harvest, whereafter the release of base cations and alkalization starts due to decomposition and mineralization of harvest residuals and other organic matter. Based on 37 years long time series from four Swedish WTH experiments, model simulations indicate an increase in the exchangeable BC pools, primarily Ca^{2+}, reaching a maximum some 5–15 years after harvest, whereafter the amounts decrease again to levels similar to or lower than at harvest. However, the differences between WTH and CH in empirical studies of exchangeable BC and ANC in soil solution cease after some 30–35 years (Zetterberg et al., 2013; Erlandsson Lampa et al., 2019; Zetterberg et al., 2016; Brandtberg and Olsson, 2012). Being among the longest WTH experimental time series in the world (Achat et al., 2015; Thiffault et al., 2011), they are still too short for making it possible to validate important processes and effects during a full boreal forest rotation. For the two most southern sites, there is still a need for 30–40 years of data for covering that and for the two most northern sites this time span exceeds 60 years. To our knowledge, the only complete time series for the subsequent forest after WTH are from New Zealand based on short-rotation (26–32 years) *Pinus radiata*, D. Don plantations (Garrett et al., 2021). Based on the initial state and nutrient capital at the site and a nutrient mass balance model, harvest intensity effects (SOH, WTH and WTH plus forest floor removal) on soil status and tree productivity after a full rotation have been studied. The data are of interest to the forestry sector for sustainable precision nutrient management and improved productivity and for the regulatory authorities as a tool for predicting nitrogen leaching (Garrett et al., .op. cit.).

3.4. The indicator lacks relevant spatiotemporal resolution

According to Akselsson et al. (2021), countermeasures against potential negative effects of WTH should be directed towards stands with $CBH_{Exc} > 0$ and where harmful effects could be expected due to poorly buffered soils with restricted BC availability. Besides not having relevant knowledge on the latter, the spatial resolution of data on mineralogy and soil chemistry is too low for estimating CBH_{Exc} at stand level. Additionally, potential negative effects, larger than those found at the time of harvest, are expected to occur first after some decades in the succeeding forest generation. Hence, any mitigation measure induced by $CBH_{Exc} > 0$ is primarily motivated by the precautionary principle. Neither the negative effects of WTH nor the positive effects of mitigation measures such as ban on WTH or adding nutrients via ash-recycling, industrial agrochemicals or rock products (Garrett et al., 2021; Akselsson et al., 2021) can be verified at the time of harvest, which is the first time when reliable BC_{Harv} and thereby CBH_{Exc} potentially could be calculated at stand level. However, during the subsequent tree generation there is plenty of time for identifying negative effects and for initiating mitigation measures if needed.

The chosen precautionary principle, related to BC depletion and acidification, should be valued against the possibility to use WTH as a mean for reducing CO_2 emissions from fossil fuels (Rogelj et al., 2018) in order to cope with the Paris agreement on climate change of global warming (UNFCC, 2015). The Swedish EPA acceptance of CBH_{Exc} within the "Natural Acidification Only" framework is here in conflict with another national environmental objective "Reduced Climate Impact" (Swedish EPA, 2021).

As of yet, mass-balance approaches such as the CBH_{Exc} indicator do not give necessary information at relevant spatiotemporal level for management guidance at stand level. In the context of soil productivity and acidification, there is also a need for complementing information on relevant indicators for classifying the vulnerability of the ecosystem to intense biomass production and harvesting based on e.g. the initial nutrient status of soils and vegetation (Table 1, Garrett et al., 2021; de Vries et al., 2021; Karltun et al., 2021; Durante et al., 2019). Within a broader definition of sustainability, including also biodiversity, water quality and climate effects, there is a need for locally derived and operationally applicable data on indicators relevant to such ecological processes (Titus et al., 2021).

3.5. Principal differences between the CL and CBH concepts

There are two important principal differences between the critical load (Nilsson and Grennfelt, 1988) and the critical biomass harvest concepts (Akselsson and Belyazid, 2018) related to their spatiotemporal span. Firstly, the original CL concept is directed towards S and N emission sources, aiming at reducing the long-range transported and geographically widespread deposition of protons and mobile anions. The CBH concept, on the contrary, aims to a local reduction of the BC export and acidity load at stand level. In boreal, nitrogen limited forests with negligible nitrification rates (Binkley and Högberg, 2016; Tamm, 1991) and restricted availability of mobile anions, the forest growth induced acidity is primarily arrested in the soil (Löfgren et al., 2017). Secondly, the positive effects of S and N emission reductions are causal and observed more or less directly in soils and water of acid sensitive areas (Forsius et al., 2021), while the differences in nutrient status and soil acidity seem to diminish by time between WTH and the SOH reference state (Achat et al., 2015; Zetterberg et al., 2016; Clarke et al., 2021).

The spatiotemporal differences between the CL and CBH concepts affect their applicability as tools for policy making. Empirically proven, CL has had an enormous political impact due to its widespread and direct effects on S and N emissions and the acidity status of soils and waters (Grennfelt et al., 2020). The CBH indicator, on the contrary, is estimated from regional data (Table 2) but applied locally. It focuses on local acidification effects potentially decreasing over time, potentially affecting the accessible amounts of forest biomass for bioenergy and climate change mitigation. The CBH concept is therefore a weak policy tool compared with CL, further strengthened by the scientific shortcomings described above.

4. Conclusion

Mass-balance methods such as the CBH_{Exc} indicator suggested for risk classification of BC depletion and acidification effects of WTH are not based on current scientific knowledge. Its value as indicator for sustainable forestry is therefore limited. The CBH_{Exc} indicator does not account for all relevant processes leading to an exaggeration of the soil sensitivity. Additionally, the large uncertainty in the input variables makes the indicator an imprecise instrument. There is a poor correlation between the CBH_{Exc} indicator between the actual forest soil status related to exchangeable BC and acidification at county level. Instead, the CBH_{Exc} indicator seems to classify productive sites as more sensitive than low productive ones. The flux data needed for calculating CBH_{Exc} indicator are complex, suffer from large uncertainties and lack possibilities for validation. The mass-balances are calculated for a full forest rotation without taking into account potential feed-back mechanisms. There are quantitatively important BC pools not accounted for by the common salt extraction methods. Hence, mass-balance approaches such as the CBH_{Exc} indicator do not give necessary information at relevant spatiotemporal level for being a scientifically reliable forestry sustainability indicator. Additionally, the selected environmental threat and the precautionary principle behind the CBH_{Exc} indicator are dubious, in conflict with and not valued against the UN and national climate change mitigation actions. Hence, there is a risk for a too restrictive policy for the use of harvest residues, negatively affecting climate as well as forest revenues.

In our opinion, mass-balances used for management guidance should only be used in combination with other types of data for assessing potential biomass harvesting effects on vegetation, soils and water. Besides well-founded data representing relevant spatial and temporal resolution, site characteristics at stand level such as soil texture, soil depth, geological origin and the nutrient levels in needles or leaves in apparent vegetation are examples of potential indicators. Combinations of such type of data may also be scientifically interesting, identifying knowledge gaps that may be important for understanding the long-term nutrient dynamics in forests.

CRediT authorship contribution statement

Stefan Löfgren: Writing – review & editing. **Johan Stendahl:** Writing – review & editing. Erik Karltun: Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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