

ELEMENT REMOVAL IN HARVESTED TREE BIOMASS: SCENARIOS FOR CRITICAL LOADS IN WALLONIA, SOUTH BELGIUM

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Abstract. The critical load concept is now widely used as a tool for developing emission control policies in Europe. As a signatory country of the Convention of Long-Range Transboundary Air Pollution, critical loads for acidity, nutrient nitrogen, nitrogen and sulphur have been calculated for the Flemish and Walloon regions in Belgium. This paper describes the methodology used for estimating critical loads for forest soils in the Walloon region according to the Steady-State Mass Balance equations. As an example the methodology was applied to the catchment 'Waroneu', situated in a sensitive area of the Haute Ardenne. Main input parameters to the equations were derived from precipitation and runoff data of the catchment study. Improved estimates of nitrogen uptake (Nu) and base cation uptake (BCu) were obtained by intensive sampling of *Picea abies* and *Quercus robur* trees. Nutrient contents (Ca, Mg, K, N) and nutrient to nitrogen ratios of *Picea abies* reflected the poor soil quality at a site with high N deposition. *Quercus robur* nutrient contents increased from stem to higher order branches with a high proportion of nutrients located in the bark. However the simulation of stem only harvesting had a minor effect on critical loads. Measured wood densities were lower than reported literature values with a main effect on Nu and BCu estimates. The use of recommended default values and/or data derived from the experimental site resulted in a wide range of critical loads, some of which were largely overestimated. Results demonstrated the importance of site specific data for critical load calculations.

Keywords: base cation uptake, Belgium, catchment, critical loads, nitrogen, *Picea abies*, *Quercus robur*

1. Introduction

The critical load concept is now widely used as a tool for developing emission control policies in Europe. A critical load can be defined as '*the maximum deposition of a given compound which will not cause long-term harmful effects on ecosystem structure and function, according to present knowledge*' (Nilsson and Grennfelt, 1988; Hornung and Skeffington, 1993). This method was first developed for the reduction of SO₂ and NO_x emissions (second sulphur Protocol, Oslo, 1994) and has since been extended to nitrogen. For each signatory country, the method consists of defining sensitive receptor ecosystems (e.g. heathlands, forests, soils, lakes, etc.) or elements of the built environment and applying empirical approaches such as soil mineralogy classes (Hornung *et al.*, 1995), vegetation indexes based on changes in



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species composition (UAB, 1996), models (De Vries *et al.*, 1992; Forsius *et al.*, 1998) or mass balance equations (Sverdrup and De Vries, 1994) for calculating the maximum permissible acid, sulphur and nitrogen deposition load. For forest soils, Steady-State Mass Balance equations (SSMB or SMB) are most frequently used. Values inserted into the critical load equations are derived from experimental data of each country, or when no specific data are available, from recommended default values (UAB, 1996). However, a range of default values is available and the choice is left to the judgement of the investigator. Furthermore, recommended values are not always representative of the actual situation at the site under study. A wide range of critical loads can therefore be derived depending on the values chosen. In particular, few data for nutrient uptake of coniferous and deciduous trees are available in the literature and these often depend on site (country) specific characteristics.

In Belgium, 23% (620000 ha) of the territory is covered by forests, with 80% of the forest area situated in the Walloon region, south Belgium. In the Walloon region, 31% of the area is forested, with ca. 50% of deciduous (mainly *Fagus* sp. and *Quercus* sp.) and 50% conifers (mainly *Picea* sp.) in the production forests (Laurent, 1997). The main forested area is situated in the Ardenne on acid Cambrian and Devonian bedrock, naturally poor in exchangeable cations, particularly magnesium. Forest dieback has been observed and has been related to increased pollution, especially nitrogen deposition, exacerbating the deficiency in magnesium (Weissen *et al.*, 1990). Hence the importance of establishing reliable critical load estimates for forest soils in the Walloon region. In particular, more reliable estimates for nutrient contents of trees growing on the poor acid forest soils in the Ardenne are needed.

As a signatory country of the Convention of Long-Range Transboundary Air Pollution, critical loads for acidity, nutrient nitrogen, nitrogen and sulphur have been calculated for the Walloon region in Belgium. In this paper, we describe the methodology used for estimating critical loads for forest soils in the Walloon region according to the Steady-State Mass Balance equations. Improved estimates for nitrogen uptake (Nu) and base cation uptake (BCu) were obtained by intensive sampling of *Picea abies* (Norway spruce) and *Quercus robur* (English oak) trees. The implication of using default or site specific data on critical load estimates will be discussed.

2. Material and Methods

2.1. STUDY SITE

Data used for critical load calculations were derived from the experimental catchment 'Waroneu', situated in the 'Hertogenwald' forest (50°34'N, 6°02'E), eastern Belgium (Dulière *et al.*, 1999). The altitude ranges from 310 to 430 m. The

acid brown soils originating from pleistocenic loess loam are characterised by the presence of pseudogley and with moder to dysmoder humus type. Soil depth varies between 0.35 and 2 m. Stony residues from the underlying Revinian bedrock (quartzites, quartzo-phyllades, phyllades) are mixed within the soil profile (Buldgen, 1984). Soils in the Haute Ardenne are naturally poor in base cations, with a base saturation of 10–15% in the mineral soil horizons (Delecour, 1978). Soil pH in the organic horizons rarely exceeds 3.5. The annual rainfall is 1300 mm and mean annual air temperature is 7 °C. Throughfall N inputs (under *Picea sp.*) are about 20 and 15 kg ha⁻¹ a⁻¹ NH₄⁺-N and NO₃⁻-N, respectively. The catchment, 83 ha, is covered by 35% with deciduous species (*Quercus sp.*, *Fagus sp.*) and 51% with conifers (*Picea abies*), the remaining being open space.

2.2. CALCULATIONS

Critical loads (CL) for forest soils were calculated according to the Steady-State Mass Balance method (SSMB), also called the Simple Mass Balance (SMB) (Werner and Spranger, 1996).

[1] critical load of actual acidity; $CL(Acac)=BCw-ANClc(crit)$

[2] critical load of potential acidity;

$$CL(Acpot)=BCw-ANClc(crit)-BCu+Ni+Nu+Nde$$

[3] critical load of sulphur; $CLmax(S)=CL(Acac)+BCdep^*-Cldep^*-BCu$

[4] critical load of nitrogen; $CLmax(N)=Ni+Nu+CLmax(S)$

[5] critical load of nutrient nitrogen; $CLnut(N)=Ni+Nu+Nle(acc)+Nde$

Where (eq ha⁻¹ a⁻¹, unless otherwise specified):

BCw: base cation weathering

ANClc(crit)=-Q([Al]crit+[H]crit): critical leaching of Acid Neutralising Capacity

BCu: mean annual net nutrient element (BC: 'base cation': Ca, Mg, K) uptake in the vegetation component which is removed from the site

Ni: annual nitrogen immobilisation in the soil

Nu: mean annual net nitrogen uptake in the vegetation component which is removed from the site

Nde: annual nitrogen flux to the atmosphere by denitrification

BCdep*: non sea salt deposition of physiological active base cations (Ca, Mg, K)

Cldep*: non sea salt deposition of chloride

Nle(acc): acceptable nitrogen leaching

Q: precipitation surplus (m³ ha⁻¹ a⁻¹)

[Al]crit: critical aluminium concentration (eq m⁻³)

[H]crit: critical proton concentration (eq m⁻³)

2.3. METHODS TO DERIVE SITE SPECIFIC PARAMETERS

2.3.1. *Element Contents in Aboveground Harvested Biomass*

2.3.1.1. *Picea abies*. Twelve trees, situated in the 'Robinette' catchment adjacent to the Waroneu catchment in the 'Hertogenwald' have been harvested in October 1996 (Dalem, 1997). Nine trees were aged 60 years (dbh at 130 cm: moy: 120 cm, min: 90 cm, max: 140 cm) and the three remaining trees were aged 90 years (dbh at 130 cm: 184, 194, 202 cm), representing the age distribution of the trees in the catchment. Ten wood sections were sampled on each tree at heights corresponding to a 'proxy' function (Gregoire *et al.*, 1987). This function ensures that the sampling frequency at a certain height is proportional to the tree diameter. More sections were therefore taken towards the base of the stem. After trimming the bark, a hole was drilled in each section towards the centre of the bole and shavings of the 10 samples for each tree mixed. The shavings were ground and dried at 65 °C. For total N content, 100 mg were digested in K₂SO₄-HgO-H₂SO₄ and analysed by steam distillation (Allen, 1989). Nutrient elements (Ca, Mg, K) were analysed by atomic absorption spectrometry (Perkin Elmer) after wet oxidation of 500 mg in HNO₃-HClO-HF (van Loon, 1985). Standard material of beech wood (Gruber *et al.*, 1996) was analysed in parallel to ensure the quality of digestion and analyses methods. The nutrient element content of each tree was then calculated from concentrations, wood density and total tree volume (estimated from bole circumference measured at 15 heights).

2.3.1.2. *Quercus robur*. Nine trees (aged 60–90 years; dbh at 130 cm: moy: 103.4 cm, min: 65 cm, max: 125 cm) were harvested in the 'Waroneu' catchment in October 1998 (Masuy, 1999). Branch order was defined according to its diameter and the appearance of the bark. Bole, first (big branches after first junction on bole), second (rough bark, 10–15 cm diam.) and third (smooth bark, 3–6 cm diam.) order branches were sampled. Four sections (base, top and 2 equidistant in between) were sampled from the bole. Three sections (base, middle, top) were sampled for the other branches, with all branches sampled from first orders and 3 branches selected at random for second and third order branches. Lengths between the sections and circumferences were measured for tree volume estimations. Infra-density is defined as the ratio [mass dry wood/volume wet wood] and was measured as defined by Ranger *et al.* (1992).

Four to five bark samples were cut from each section and samples were dried at 37 °C, ground and freeze-dried. After trimming the bark, a hole was drilled in each wood section (bole and branches) towards the centre along three radii. Shavings were freeze dried before analyses.

Samples, approximately 1g, were dry-ashed at 450 °C, then dissolved in HNO₃ (Glineur, 1998). Two digestions were performed for each sample and analysed separately. Nutrient elements (Ca, Mg, K) were determined by ICP-AES (VARIAN VISTA). For total N content, 200 mg were digested in K₂SO₄-HgO-H₂SO₄ (Allen,

1989) and analysed by colorimetry. Standard material of beech wood (Gruber *et al.*, 1996) was analysed in parallel to ensure the quality of digestion and analyses methods.

Mean contents for the bole and the different branch orders of wood and bark were calculated for each tree. Significant differences were then tested by analyses of variance (Proc GLM, SAS) followed by Tukey's studentised range test (SAS Institute Inc., 1989). The nutrient element content of each tree was then calculated from concentrations, wood density and total tree volume (estimated from bole and branch circumferences). Due to the labour intensive nature of the analyses involved, six trees (dbh at 130 cm: moy: 94.4 cm, min: 65 cm, max: 121 cm) were analysed for chemical composition.

2.3.2. *Q*

Precipitation surplus was defined as the amount of water leaving the catchment at streamwater runoff. The yearly water flux ($\text{m}^3\text{ha}^{-1} \text{a}^{-1}$; May 1998-May 1999) at runoff from the Waroneu catchment was determined using an ISCO 32-20 auto-sampler, measuring water flow continuously.

2.3.3. *BCdep** and *Cldep**

Non sea salt deposition of Ca, Mg, K and Cl was calculated from throughfall concentrations and volumes. Although for some ions canopy leaching occurs, throughfall measurements represent the actual input of these ions to the soil. Furthermore, in the absence of real deposition data, throughfall may be a good approximation of deposition, as bulk rainfall data would neglect dry deposition inputs. Yearly fluxes (May 1998-May 1999) of base cation and chloride deposition have been calculated by multiplying throughfall volumes by concentrations. Samples were taken at monthly intervals from 4 throughfall samplers, each consisting of five funnels placed at 40 cm height (total surface of 5 funnels: 369.5 cm^2). The funnel was protected from falling leaves by a nylon net and connected to collecting bottles which were inserted into the ground (Rodda *et al.*, 1985). Stemflow was assumed negligible, as it represents less than 1% of total precipitation for oak (Nizinski and Saugier, 1988). Seasalt correction has been applied as follows

$$X_{\text{dep}}^* = X_{\text{dep}} - N_{\text{dep}}^* (X_{\text{sw}}/N_{\text{sw}})$$

With

X: SO_x, Ca, Mg, K, Cl; X_{dep}, N_{dep}: total deposition of X, Na; X_{dep}*: corrected deposition of X; X_{sw}/N_{sw}: ratio X/Na in seawater (for S: 0.12, Mg: 0.227, Ca: 0.044, K: 0.021, Cl: 1.164)

For Cl, seasalt correction resulted in a negative value. Cl_{dep}* has therefore been set equal to zero.

TABLE I

Nutrient contents (mg kg^{-1}) and infra-density (g cm^{-3}) in the stem of *Picea abies* (mean and sd, $n=12$) from this study (Robinette) and literature values

	Tree age (years)	Infra-density	Ca	Mg	K	N
Stem Robinette	60–90	0.36	604.7 (95.9)	104.9 (43.6)	644.1 (106.8)	791.6 (19)
(Fober, 1977)	100		870	–	200	880
(Nys <i>et al.</i> , 1983)	50		700	100	400	800
(Le Goaster <i>et al.</i> , 1991)	85		700	100	400	900
(Ranger <i>et al.</i> , 1992)	85		600	130	400	600

2.3.4. *Nle(acc)*

Acceptable nitrogen leaching was defined as ($\text{N-NH}_4 + \text{N-NO}_3$) at streamwater runoff. Fluxes were measured from 2-weekly samples (consisting of daily samples reconstituted according to flow volume), analysed by HPLC and colorimetry for nitrate and ammonium, respectively.

3. Results and Discussion

3.1. ELEMENT CONTENTS IN ABOVEGROUND HARVESTED BIOMASS

3.1.1. *Picea abies*

Nutrient element contents in the stem of *Picea abies* were in the same order of magnitude than reported literature values from *Picea abies* on poor sites in the Ardennes or Vogues (Tables I, II).

Wood infra-density was relatively low and could be the result of pollution and nutrient stresses on the *Picea abies* trees at Robinette. At our site, crown development, a primary regulator of basic density (Lindstrom, 1996), might have been affected by air pollution. Similarly, Sander *et al.* (1995) showed a decrease in wood density from 0.7 g m^{-3} in 1960 to below 0.5 g m^{-3} in 1980–1990, attributed to air pollution. However, our density values for stemwood were within the range of recommended densities for coniferous trees ($0.4\text{--}0.5 \text{ g cm}^{-3}$; UAB, 1996).

Nutrient to nitrogen ratios (Table III) were close to default values recommended in the Manual of Methods (UAB, 1996). Calcium and magnesium to nitrogen ratios were slightly lower, reflecting the poor nutrient status of the site and the sufficient nitrogen availability.

TABLE II
Nutrient contents of *Picea abies* stemwood
(Robinette; eq m⁻³)

Ca	Mg	K	N
11.8	3.4	6.4	22.1

TABLE III
Nutrient to nitrogen ratios (eq eq⁻¹) in *Picea abies*
and default values (UAB, 1996)

	Ca:N	Mg:N	K:N	BC:N
Robinette	0.53	0.15	0.29	0.98
Default values	0.6	0.2	0.2	0.9

TABLE IV
Nutrient contents (mg kg⁻¹) and infra-densities (g cm⁻³) in wood and bark of
Quercus robur (mean and sd, n=6). Different letters denote significant differences
at p<0.05

	order	Infra-density	Ca	Mg	K	N
Wood	Stem	0.63	294.4 a (38.3)	18.8 a (6.8)	415.1 a (168.8)	1101.4 a (211.7)
	I	0.63	347.2 a (75.4)	29 a (13.4)	497.2 a (222.2)	1173.1 a (78.3)
	II	0.61	474.5 b (84.8)	57.2 a (27.4)	685.7 ab (261.7)	1409.5 a (172.2)
	III	0.59	660 c (61.8)	123.3 b (38.7)	1036.4 b (312.1)	2101.1 b (563.6)
Bark	Stem	0.45	15751.2. a (4407.3)	242.5 a (58.3)	1158.7 a (450.4)	5327.9 a (633.8)
	I	0.44	13071.9 a (4077.6)	275.5 ab (61.5)	1275.3 a (295.4)	5833.7 a (728.5)
	II	0.48	11806.1 (3679.3)	324.3 ab (63.1)	1308.5a (268.7)	6048 a (769.3)
	III	0.46	9709.9 a (2507.6)	372.4 b (58.7)	1337.2 a (301.5)	6330.3 a (704.3)

TABLE V
Nutrient to nitrogen ratios for *Quercus sp.* wood and literature values (eq eq⁻¹)

	Ca/N	Mg/N	K/N	BC/N
Waroneu <i>Quercus robur</i>	0.19	0.02	0.13	0.34
(Allen, 1989) <i>Quercus petraea</i> (inner heartwood)	0.42	0.11	0.21	
(Glineur, 1998) <i>Quercus robur</i> (inner heartwood)	0.17	0.06	0.18	

3.1.2. *Quercus robur*

Our infra-density values for oak stemwood (Tables IV, VI) were within the range of recommended densities for deciduous trees (0.55-0.70 g cm⁻³; UBA, 1996). Values were however significantly lower than the 0.9 g cm⁻³ reported by Duvigneaud *et al.* (1969). Varying values of wood density however may influence significantly parameter estimates for critical load equations. Nutrient contents increased from stem to higher order branchwood (Table IV). For all elements and branch orders, bark concentrations were significantly higher than wood concentrations, except for K in stem and branch order III. Nutrient concentrations were notably lower than for *Quercus robur* on a more nutrient rich site (Levy *et al.*, 1996). When compared to similar sites in the Netherlands (De Visser, 1992) or in the Belgian Ardenne (Glineur, 1998), nutrient contents were also lower in our study, in particular for magnesium.

Nutrient to nitrogen ratios (Table V) were low compared to ratios for *Quercus petraea* calculated from (Allen, 1989). They were however close to values for *Quercus robur* from a similar site in the Ardenne (Glineur, 1998).

Stem and first order branches represented near 82% of total tree volume (Table VI). The percentage of bark increased from stem (15.5%) to third order (44.1%) branches. Due to its high nutrient concentrations, the bark contained the highest proportion of nutrients (except for K) of the harvested tree biomass (Table VII). For example, 87% of Ca and 80% of (Ca+K+Mg) from stem and branches were located in the bark.

3.2. Nu AND BCu VALUES DERIVED FROM THIS STUDY

In the critical loads framework, the long term net growth uptake of nutrient elements (BC=Ca, Mg, K) and of nitrogen (N) is assumed to be equal to the removal in harvested biomass. Nu and BCu values therefore do not represent the uptake of these elements by the tree, but their element content in harvested biomass meaned over the rotation period (UAB, 1996). In this paper, Nu and BCu were calculated from measured Ca, Mg, K or N contents removed in harvested biomass, divided by the age of the tree and calculated for one hectare. For the mixed watershed Waroneu (83 ha), BCu and Nu values for were calculated using a tree volume of 3942 m³

TABLE VI

Volume, percentage of total tree volume, percentage of bark on each order and infra-densities (g cm^{-3}) of *Quercus robur* trees in stem (S) and branches of order I–III (n=9, std in brackets)

Order	Volume (m^3)	% of total volume	% bark	Infra-density wood	Infra-density bark
S	0.7881 (0.482)	60.8	15.5	0.63	0.45
I	0.2700 (0.1467)	20.8	19.9	0.63	0.44
II	0.1598 (0.0719)	12.3	27.3	0.61	0.48
III	0.0787 (0.0392)	6.1	44.1	0.59	0.46

TABLE VII

Nutrient content of *Quercus robur* wood and bark

	Bark (eq m^{-3})	Wood (eq m^{-3})	Total (eq m^{-3})	% of nutrient in bark	Bark (mg kg^{-1})	Wood (mg kg^{-1})
Ca	60.7	8.5	69.2	87.4	2679.2	273
K	2.8	6.3	9.1	30.7	242.2	391
Mg	2.1	1.2	3.3	63.4	55.35	23.5
BC	65.6	16	81.6	80.1	–	–
N	36.3	42.8	79.1	45.9	1118.7	956.5

for *Quercus robur* (coverage 35%) and 12940 m^3 for *Picea abies* (coverage 51%). BCu and Nu values were also calculated assuming a coverage of 100% of *Quercus robur* (stem only or stem and bark harvesting) or *Picea abies*.

TABLE VIII

Nutrient element contents (eq ha^{-1}), Nu and BCu values obtained in this study ($\text{eq ha}^{-1} \text{ a}^{-1}$)

	Ca	Mg	K	N	BCu	Nu
Waroneu	5127.7	688.5	1428.7	7202.3	96	96
100% oak	9394.5	444.7	1230.7	10733.3	147	143
100% oak stem only	1157.2	164.2	849.7	5801	28	77
100% spruce	3606.7	1039.5	1956.7	6756	88	90

TABLE IX

Recommended default values (Werner and Spranger, 1996) and values derived from site specific data (in bold) used for critical load calculations. ¹Calculated from nutrient concentrations: Ca= 776 mg kg⁻¹, Mg= 72 mg kg⁻¹, K= 164 mg kg⁻¹, wood density=0.9, tree density: 136 m³ ha⁻¹ (Duvigneaud et al., 1969); eq ha⁻¹ a⁻¹ unless otherwise specified

Parameter	Value
Nu	248 (temperate coniferous minimum value), 267 (temperate broadleaf minimum value), 885 (temperate coniferous maximum value), 1142 (temperate broadleaf maximum value), 96 (Waroneu), 143 (oak only), 77 (oak stem only), 90 (spruce only)
Ni	35.7
Nde	71.4
[Al]crit	0.0095 eq m ⁻³
[H]crit	0.1 eq m ⁻³
BCw	122.74 (eq ha ⁻¹ a ⁻¹ 0.5 m ⁻¹)
BCu(oak) ¹	80 ¹ , 96.6 (Waroneu), 147.6 (oak only), 29 (oak stem only), 88 (spruce only)
Nle(acc)	71.4 (managed coniferous), 214 (intensive managed coniferous) 299.4
BCdep*	1358
Cldep*	0
Q	7231 m ³ ha ⁻¹ a ⁻¹

3.3. CRITICAL LOADS CALCULATIONS

3.3.1. Summary of Parameter Values used for Critical Loads Calculations

Recommended default values and parameter values obtained in this study used in the following CL calculations are listed in Table IX. In the following calculations, default values were compared to site specific values (Nu, BCu, Nle_{acc}) or used when site specific data were not available.

The critical Al concentration ([Al]crit) was obtained by specifying a critical pH of 4 ([H]crit=0.1 eq m⁻³) and a Kgibb of 9.5 m⁶eq⁻², as suggested for organic soils (UBA, 1996). These values have then been substituted in:

$$[Al]=Kgibb*[H]^3$$

Ni and Nde values were chosen in the lower range according to the poor soil quality and the precautionary principle. BCw was chosen as recommended for acidic parent material and a texture class 1 (clay content<18%).

3.3.2. Critical Load of Actual Acidity

$$CL(Acac)=BCw+Q([Al]crit+[H]crit)=915 \text{ (eq ha}^{-1} \text{ a}^{-1}\text{)}$$

3.3.3. Critical Load of Potential Acidity

$$CL(\text{Acpot}) = \text{BCw} + Q(9.5 * [0.1]^3 + 0.1) - \text{BCu} + \text{Ni} + \text{Nu} + \text{Nde} = 1030 \text{ (eq ha}^{-1} \text{ a}^{-1}\text{)}$$

CL(Acpot) was dominated by the second term of the equation, ANCle(crit), which was dominated by the water flux leaving the catchment (Q). The estimation of ANCle(crit) and BCw could be improved (reduced) by establishing a site specific relationship between aluminium and pH, through field and laboratory experiments. Nu and BCu (site specific values) had a minor influence, because of their antagonistic effect, but their relative importance could be influenced by forestry management practices. For example for *Quercus* sp., stem only harvest causes a more important reduction in BCu (147.6 to 29 eq ha⁻¹ a⁻¹) compared to Nu (143.1 to 77.3 eq ha⁻¹ a⁻¹), leading to an increase in CL(Acpot). Furthermore, the equation does not take into account the influence of stand rotation. Soils in the Haute Ardenne are considered oligotroph and plantations rely on recycling of nutrients from the organic horizons (Buldgen, 1984). On such nutrient poor sites BCw is low and the change in BCu and Nu in rapid rotations would be low relative to the magnitude of the ANCle term. Therefore rapid rotations would only have a minor influence on CL(Acpot), not reflecting a possible impoverishment of the soil.

Proton deposition at Waroneu in throughfall was 490 eq ha⁻¹ a⁻¹ and, with the current calculation methods, critical loads of acid deposition were not exceeded.

3.3.4. Critical Load of Sulphur

$$CL_{\text{max}}(\text{S}) = CL(\text{Aac}) + \text{BC}_{\text{dep}} * -\text{Cl}_{\text{dep}} * -\text{BCu} = 2177 \text{ (eq ha}^{-1} \text{ a}^{-1}\text{)}$$

Table X illustrates the minor influence of various BCu values on the critical sulphur load estimations. At our site CLmin(S) has to be taken into account as CLnut(N) < CLmax(N) (see below). With an S deposition in throughfall of 1912 eq ha⁻¹ a⁻¹, Waroneu is slightly above the critical load calculated (1878 eq ha⁻¹ a⁻¹). On the same site covered only with oak, stem only harvesting would enhance the critical load and the same sulphur deposition would then seem acceptable. Therefore, despite the small contribution of BCu in the equation, management practices may influence critical loads of sulphur and pollution abatement strategies.

3.3.5. Critical Load of Nitrogen

$$CL_{\text{max}}(\text{N}) = \text{Ni} + \text{Nu} + CL_{\text{max}}(\text{S}) = 2309 \text{ (eq ha}^{-1} \text{ a}^{-1}\text{)}$$

3.3.6. Critical Load of Nutrient Nitrogen

$$CL_{\text{nut}}(\text{N}) = \text{Ni} + \text{Nu} + \text{Nle}(\text{acc}) + \text{Nde} = 502 \text{ (eq ha}^{-1} \text{ a}^{-1}\text{)}$$

CLnut(N) is lower than CLmax(N), therefore the former should be considered for exceedance calculations. Varying Nle values (Table IX) has an important influence on CLnut(N). Using the minimum recommended value of 71.4 (kg ha⁻¹ a⁻¹)

TABLE X

Influence of different BCu values on the estimation of CLmax(S) (eq ha⁻¹ a⁻¹). CLmin(S)=CLmax(S)-Nle (see below)

	BCu	CLmax(S)	CLmin(S)
Waroneu	96	2177	1878
100% oak	147	2126	1827
100% oak stem only	29	2245	1946
100% spruce	88	2154	1855
Literature oak	80	2194	1895

TABLE XI

Influence of different literature default and site specific (bold) Nu and Nle values (see Table IX) on the estimation of CLnut(N) (eq ha⁻¹ a⁻¹)

	Nle	CLnut (N)	
Waroneu	299	502	(calculated with the Nu of the site : 96)
Managed coniferous	71	274	
Intensive managed coniferous	214	417	
	Nu		
Waroneu	96	502	(calculated with the Nle of the site : 299)
100% oak	143	549	
100% oak stem only	77	483	
100% spruce	90	496	
Temperate coniferous min	248 (rotation 75 y)	654	
Temperate coniferous max	885	1291	
Temperate broadleaf min	267	673	
Temperate broadleaf max	1142	1548	
Minimum Nle (71) and Nu (96)		274	
Maximum Nle (299) and Nu (1142)		1549	

yields a CLnut(N) of 274. In contrast, the use of site Nle ($4.2 \text{ kg ha}^{-1} \text{ a}^{-1}$) leads to a higher CLnut(N) of 502. However, N leaching values at Waroneu may already represent 'N-saturated' conditions, even if streamwater nitrate concentrations are still within an acceptable range (5 mg l^{-1}). The use of lower recommended values may therefore be preferable.

As for CLmax(S), the use of Nu calculated for Waroneu or simulated for different management and oak or spruce only coverage, has a minor influence on CLnut(N) ($486\text{-}549 \text{ eq ha}^{-1} \text{ a}^{-1}$). This may however be attributed to low wood (oak: 0.615, spruce: 0.4) and tree (oak : $40\text{-}50 \text{ stems ha}^{-1}$ spruce : $250 \text{ stems ha}^{-1}$) densities. The use of recommended minimum or maximum Nu values resulted in a doubling of the estimated critical load (Table XI). In any case, recommended values largely overestimated CLnut(N) for Waroneu, stressing the necessity of using site specific data.

N deposition at the site was $2316 \text{ eq ha}^{-1} \text{ a}^{-1}$ and the critical load of nitrogen was largely exceeded with any scenario.

4. Conclusions

The application of the steady state mass balance critical loads methodology to data derived from an experimental forested catchment situated in a sensitive area of the Haute Ardenne region demonstrated the importance of site specific data for critical load calculations. Improved estimates of BCu and Nu were obtained by measuring element contents in aboveground harvested biomass of *Picea abies* and *Quercus robur*. The major proportion of the nutrient pool of the aboveground harvested biomass of *Quercus robur* was situated in the bark. The use of recommended default values and/or data derived from the experimental site resulted in a wide range of critical loads, some of which were largely overestimated. The contribution of BCu and Nu for the calculation of CLmax(S) and CLmax(N) was low. These two critical loads were dominated by the importance given to ANCle(crit), a highly speculative parameter, in the equation. Despite the low tree density at our experimental catchment, the range of critical loads obtained with various Nu values was particularly wide for CLnut(N). This is a crucial value, considering the high N deposition thought responsible for the observed forest dieback in this region.

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