| | |
|---|---|
| Til: | Norges vassdrags- og energidirektorat (NVE) |
| v/: | Aart Verhage |
| Kopi til: | |
| Dato: | 2016-12-09 |
| Rev.nr. / Rev.dato: | 0/ |
| Dokumentnr.: | 20150457-04-TN |
| Prosjekt: | Nye aktsomhetskart snøskred |
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# Forest cover within *Nye aktsomhetskart snøskred i Norge* (NAKSIN)

**Sammendrag** / ***Abstract***
This technical note describes a first approach to classify forest stands in Norway in respect to their protective effect against natural avalanche release based on SAT-SKOG data (Sat-Skog, 2016). It specifies the use of forest data derived from SAT-SKOG producing a new map indicating potential snow-avalanche danger for a limited area. SAT-SKOG is a generally accessible data set on forest properties covering (almost) all of Norway. It does not directly contain the quantities of interest for the purpose of estimating the effect of forest stands on the release probability or run-out distance of avalanches, namely the number of trees per unit area, $N$, and the average diameter at breast height, $d_{1.3}$. However, $N$ and $d_{1.3}$ can be approximated from the available data by applying well-established relations about tree growth. Layers of $N$ and $d_{1.3}$ for all of Norway can be prepared and loaded into the project NAKSIN (Nye AktsomhetsKart for Snøskred I Norge – New hazard indication maps for snow avalanches in Norway). These two forest stand parameters can be used to classify the protective effective of forest against avalanches. The proposed classification is a rather conservative approach having an overall annual avalanche probability of 1/1000 for indication map in focus and keeping in mind that no direct field investigations are involved.

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# 1 Scope of the present document

It is widely accepted that a dense forest has a protective effect against avalanche release (Olschewski and others, 2012; Bebi and others, 2001). The protective effect is on the one hand side caused directly due to the support of the snowpack by tree trunks and on the other hand by a change in the snowpack properties, e.g. by reducing the formation of continuous weak layers that contribute to slab avalanches (Gubler and Rychetnik, 1991; Teich and others, 2016). Less well established are the specific criteria to ensure sufficient safety. Likewise, there is little knowledge about the (protective) effect of a forest after an avalanche has released Anderson and McClung (2012).

SAT-SKOG is a generally accessible data set on forest properties covering (almost) all of Norway. It does not directly contain the quantities of interest for the purpose of estimating the effect of forest stands on the release probability or run-out distance of avalanches, namely the number of trees per unit area, $N$, and the average diameter at breast height, $d_{1.3}$. However, $N$ and $d_{1.3}$ can be approximated from the available data by applying well-established relations on tree growth. Layers of $N$ and $d_{1.3}$ for all of Norway can be prepared and loaded into the project NAKSIN (Nye AktsomhetsKart for Snøskred I Norge – New hazard indication maps for snow avalanches in Norway).

# 2 SAT-SKOG data

SAT-SKOG is a forest map that provides an overview of forest resources and gives information on tree species, age, and volume. SAT-SKOG is published by the Norwegian Forest and Landscape Institute (NIBIO). The maps are based on an automatic interpretation of field data from the Norwegian forest inventory and satellite images (Norsk institutt for skog og landskap, 2014).

In this approach, a forest is defined as an area of 0.1 ha (1000 m$^2$) with at least 6 evenly distribute trees that are or can reach a height of 5 m or more.

This section describes briefly the derivation of some basic forest stand parameters used afterwards in the assessment of the protective effectiveness of forest stands against natural avalanche releases based on the available SAT-SKOG data, especially:

**VUPRHA:** total timber volume per hectare (without bark);

**AGE:** average age at the record date;

**BONITET:** appraisement class (quality class) of the prevailing tree species ($H_{40}$ BONITET). The $H_{40}$ BONITET is defined as the height of a tree at the breast height age $a_{1.3} = a - a_{1.3_0}$, where $a_{1.3_0}$ is the age at which the tree reached first breast height. Hence, BONITET $H_{40}$14 means that the tree will reach a height of 14 m at $a_{1.3} = 40$ yrs. The bonitet is species specific and a high bonitet implies a high growth rate for a given species under the given environmental conditions.

**TRESLAG:** prevailing species: *Grandominert, Furudominert, Lauvdominert, Barblanding, Blanding or Ikke tresatt*

In this first approach, the derivation of the forest parameters employ several simplifying assumption:

- homogenous tree stand;
- neglecting the difference between volume with and without bark (this can be avoided by increasing the VUPRHA by 10 to 20%, however neglecting should give a more conservative approach);
- Mitchell's growth equation, that is $d_{1.3}$ increase linearly with $a_{1.3}$. This might not be totaly the cause through out the whole life cycle of a tree, but gives a reasonably good first approximation.
- use of commonly proposed empirical formulas for height and volume of a single tree.
- distinguishing only between three species spruce (S, picea), pine (P, pinus) and birch (B, betula).

The final parameter values may slightly vary if different empirical formulas are used, but this is thought negligible with respect to the overall uncertainties.

Hereafter, the following symbols are used:

*Table 1 List of symbols describing forest parameters*

| symbol | unit | description |
|---|---|---|
| a | yr | total age of the tree |
| $a_{1.3}$ | yr | breast height age |
| $a_{1.3_0}$ | yr | age at which the tree reached first breast height |
| BHD | cm | breast height (≈ 1.3 m above ground) diameter of the trunk |
| $d_{1.3}$ | m | breast height (≈ 1.3 m above ground) diameter of the trunk |
| CC | - | crown cover |
| fz | - | form factor |
| $h$ | m | tree height |
| $N$ | $m^2$ | number of trees per square meter |
| $N_{ha}$ | $ha^{-1}$ | number of trees per hectare (10000 $m^2$) |
| $v$ | $dm^3$ | volume of a single tree ($10^{-3}$ $m^3$) |
| $V$ | $m^3$ | volume per hectare |

## 2.1 Tree diameter and tree height

The diameter and height of a tree depends on its age and the growing conditions. It is common to relate tree height to the diameter or to age. There are various empirical formulas that describe these relationships (e.g. Widlowski and others, 2003). In this case, some proposed relationships that relate the tree height (in m) to BHD (in cm) are deployed.

$$h_B(\mathrm{BHD}) = 1.3 + 32.1\exp(-16.36/\mathrm{BHD} - 10.76/\mathrm{BHD}^2)\,, \quad (1)$$
$$h_S(\mathrm{BHD}) = 1.3 + 47.0\exp(-19.5/\mathrm{BHD})\,, \quad (2)$$
$$h_P(\mathrm{BHD}) = 1.3 + 50.532\exp(-24.88/\mathrm{BHD})\,, \quad (3)$$

where $h_B$ is the height of a birch tree, $h_S$ of a spruce, and $h_P$ that of a pine tree. Finally, Mitchell's approximation (Mitchell, 1976) is used to relate the BHD to the age, a, of a tree

$$\mathrm{BHD} = f_g\,\mathrm{a}_{1.3}\,, \quad (4)$$

where $\mathrm{a}_{1.3} = \mathrm{a} - \mathrm{a}_{1.3_0}$ and $\mathrm{a}_{1.3_0}$ is the age at which the tree reached breast height. The growth factor, $f_g$, can be estimated using the appraisement classes. To this end Eq. (1),

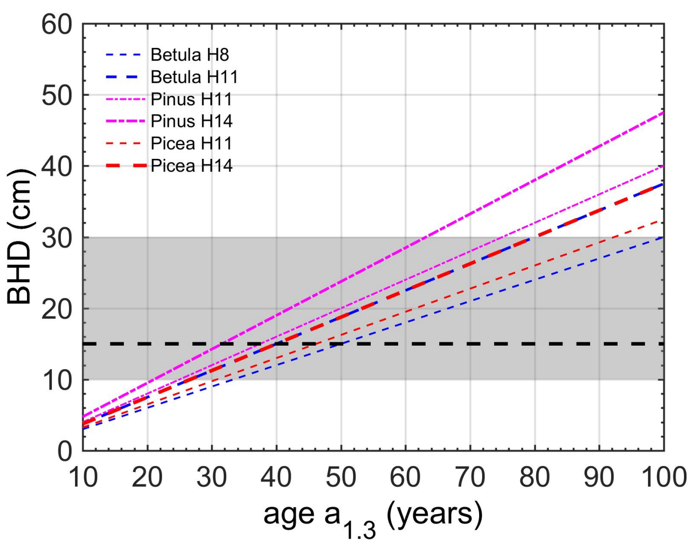


*Figure 1 BHD versus age for different appraisement classes $H_{40}$. The black dashed line shows the commonly proposed lower threshold for the tree diameter effective for avalanche protection. The grey shaded area depicts the diameter range in which trees are typically very vulnerable for breakage.*

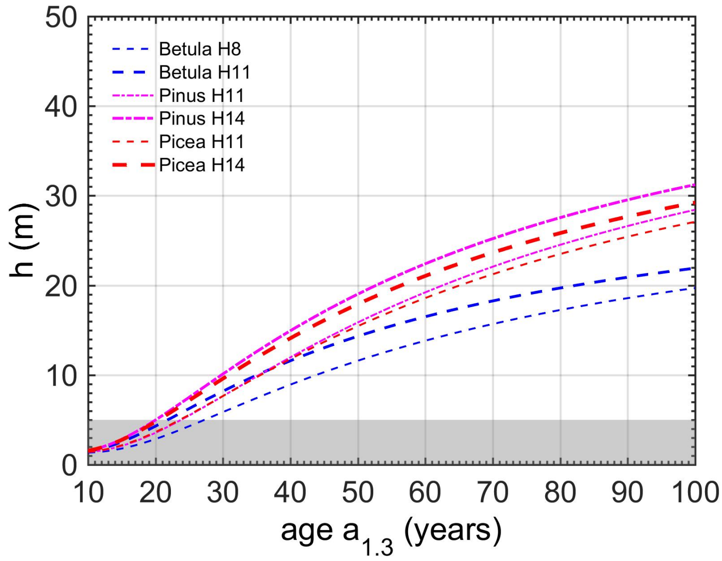


*Figure 2 $h$ versus age for different appraisement classes $H_{40}$. The grey shaded area depicts the 95% percentile of the expected 100 year maximum snow depth for Norway.*

(2), and (3) are resolved for BHD using the height according to the BONITET $H_{40}$ and than calculating $f_g = \mathrm{BHD}/(40\ \mathrm{yrs})$. Figures 1 shows an example of growth curves depending on species and appraisement classes. The corresponding tree height curves are shown in Figure 2.

## 2.2 Tree volume calculations

Commonly, the volume of a single tree is calculate as

$$v = \mathrm{fz}\frac{\pi}{4}d_{1.3}^2\, h\,, \tag{5}$$

where $d_{1.3}$ is the tree diameter measured at about 1.3 m above ground (at breast height) and $h$ is the height of the tree. The form factor, fz, depends on the species and environmental factors. For a cylinder $\mathrm{fz} = 1$, for a cylinder pyramid $\mathrm{fz} = 1/3$ and for truncated cone $\mathrm{fz} = 1/3\,(1 + a_1 + a_1^2)$, where $a_1$ is the ratio between top and bottom radius. There exist various empirical volume equations for each tree species and regions. Some of the proposed relations can be found in (Zianis and others, 2005). Here, the well-known approaches according to (Näselund, 1940) are used as a first approximation:

$$v_S(\mathrm{BHD}, h) = c_{v1}\,\mathrm{BHD}^2 + c_{v2}\,\mathrm{BHD}^2\,h + c_{v3}\,\mathrm{BHD}\,h^2 + c_{v4}\,h^2\,, \tag{6}$$

where $v$ is the volume of a tree and the relation is given for trees with bark. The parameter values for the three species are given in Table 2, where the volume is given $dm^3$, while BHD is measured in cm and $h$ in m.

*Table 2 Parameterization used in equations (6).*

| species | $c_{v1}$ | $c_{v2}$ | $b_{v3}$ | $c_{v4}$ |
|---|---|---|---|---|
| Birch (betula) | 0.03715 | 0.02892 | 0.004983 | 0 |
| Spruce (picea) | 0.1202 | 0.01504 | 0.02341 | - 0.0659 |
| Pine (pinus) | 0.09314 | 0.03069 | 0.002818 | 0 |

## 2.3 Stand density

The stand density is a determining factor by accounting for the support of the snow cover due to trees. The number of trees per area can be estimated based on SAT-SKOG data assuming a relatively homogenous forest stand. In this case, the number of tree per hectare is given by

$$N_{ha} = \frac{V_{ha}}{v_{tree}} \qquad [1/\text{ha}], \qquad (7)$$

where $v_{tree}$ is the volume of a single tree and $V_{ha}$ the volume of timber per hectare. An approximation of the mean distance between neighboring trees can be obtained by

$$D_t = \sqrt{\frac{10^4}{N_{ha}}} \qquad [\text{m}]. \qquad (8)$$

Using the equations (5) to (7), one obtains relationship between the number of trees per area and age for a given timber volume and appraisement class. Figure 3 plots an example for an appraisement class $H_{40}10$ and a given timber volume $V_{ha} = 100$ m$^3$/ha. (This does not imply that a homogenous forest stand will produce this volume at all ages). In addition, the plot depicts a fit for spruce trees following the relation

$$N_{ha} = V_{ha}\, 10^{b_1}\, \mathrm{a}_{1.3}^{b_2} \qquad [1/\text{ha}], \qquad (9)$$

where the coefficients $b_1$ and $b_2$ depend on the appraisement class and the reference volume.

## 2.4 Forest stand parameter $d\,N$

Similarly to the stand density, one obtains a relationship between the factor $d\,N$ and the age for a given timber volume and appraisement class. The factor $d\,N$ enters as an important parameter the resistent term in avalanche models as well as in the relationships that describe the effect of a forest on the stabilization of a snowpack.

According to Newton's third law, the force per square meter that trees impinge on an moving avalanche or in the static case on the snowpack can be written as (cf. Jóhannesson and others, 2009, chapt 12.1)

$$F_{tree} = \rho\, dN\, h_s \left( C_D + \frac{f_s}{\mathrm{Fr}^2} \right) \frac{U^2}{2} \tag{10}$$

where $\rho$ is the density of the (flowing) snow, $h_s$ the height of the (flowing) snow normal to the ground, $C_D$ the drag coefficient, and $U$ the velocity of the avalanche. Here, $N$ is the number of trees per square meter and $d$ their diameter. The Froude number is $\mathrm{Fr} = U/\sqrt{g h_s}$ and $g$ is the gravitational acceleration. In the static case ($\lim U \to 0$), (10) approaches

$$F_{tree} = \rho\, dN\, f_s\, g\, \frac{h_s^2}{2} \tag{11}$$

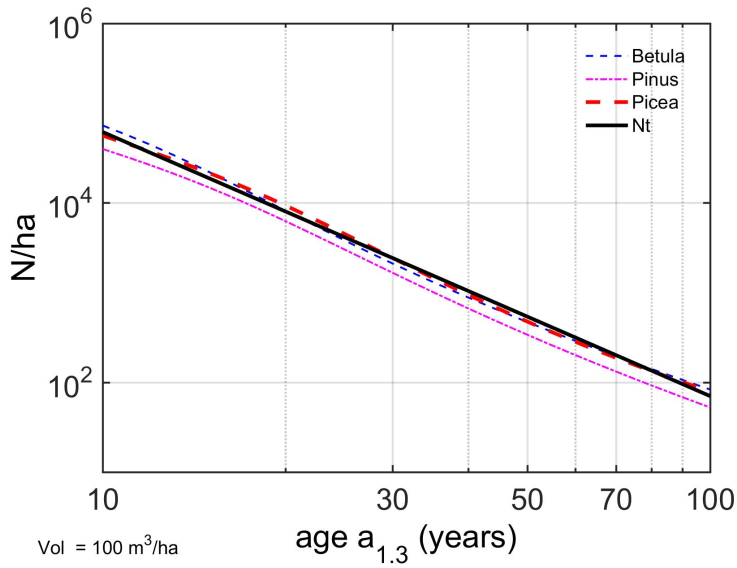


*Figure 3 Number of trees per ha versus age, $a_{1.3}$, for appraisement class $H_{40}12$ and $V_{ha} = 100$ $m^3$/ha. The line Nt gives a fit for spruce trees.*

and the parameter $f_s$ describes the influence of a tree on the snowpack the static case. It is reasonable to assume that $f_s$ is a function of parameters like HS and $d_{1.3}$ etc.

Figure 4 shows an example of the relationship between $dN$ and age $a_{1.3}$. The given fit for spruce trees follows the relation

$$dN = V_{ha}\, 10^{c_1}\, a_{1.3}^{c_2} \qquad [m^{-1}], \qquad (12)$$

where the coefficients $c_1$ and $c_2$ depend on the appraisement class and the reference volume.

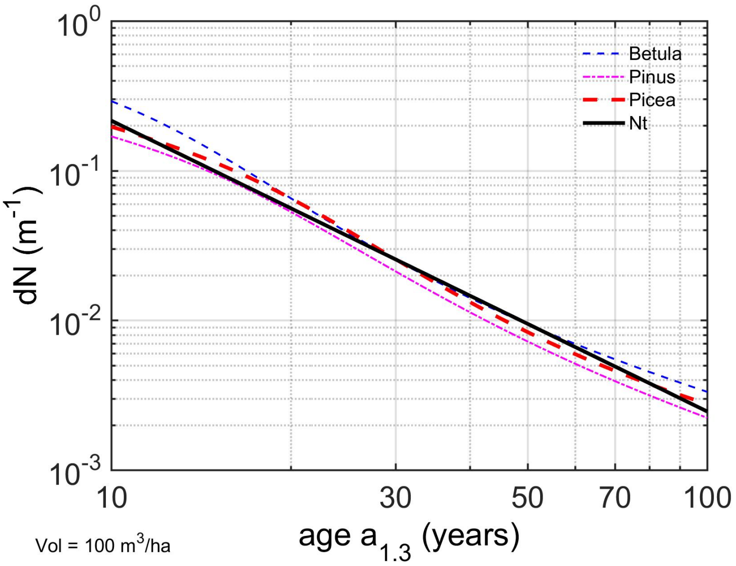


*Figure 4 Number of trees per ha versus age for appraisement class* $H_{40}12$ *and* $V_{ha} = 100$ $m^3$*/ha. The line Nt gives a fit spruce trees.*

Figure 5 plots the volume per ha as function of $N_{ha}$ and $d\,N$ for spruce and birch. The plot for pine trees looks quite similar to that for spruce.

## 2.5 Parameterization

For simplification $N_{ha}$ and $dN$ can be parameterized according equations (9) and (12) where the coefficients are given by

$$b_1 \approx b_{12}H_{40} + b_{11} \qquad (13)$$
$$b_2 \approx b_{22}H_{40} + b_{21} \qquad (14)$$

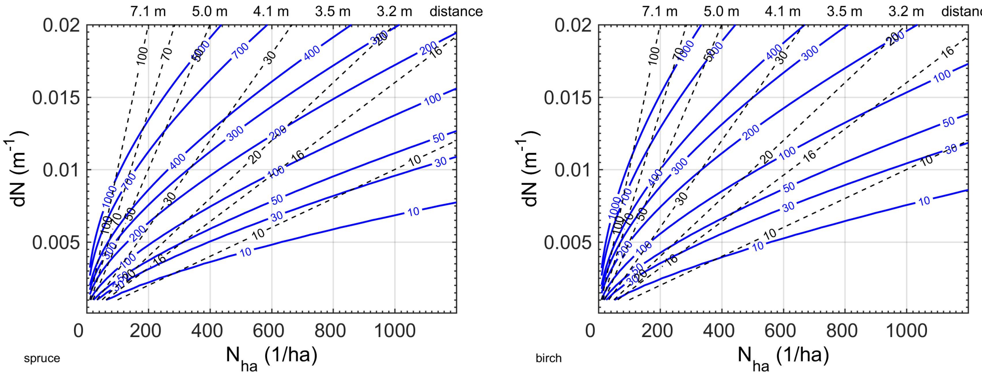


*Figure 5 Volume per ha (blue iso-lines) as function of $N_{ha}$ and $dN$ for spruce (left panel) and birch (right panel). In addition the corresponding BHD are shown (in cm; dashed lines). The top axis shows the equivalent distance between trees according Eq. (8).*

and

$$c_1 \approx c_{12}H_{40} + c_{11} \quad (15)$$
$$c_2 \approx c_{22}H_{40} + c_{21} \quad (16)$$

depending on the appraisement class $H_{40}$. Table 3 gives the corresponding parameter values for the three species.

*Table 3 Parameterization used in equations (13)–(16). The parameter are thought to be valid in the for range $H_{40}5$ to $H_{40}15$ and in the case of spruce or pine, for BHD $> 10$ cm.*

| species | $b_{12}$ (m-1) | $b_{11}$ | $b_{22}$ (m-1) | $b_{21}$ | $c_{12}$ (m-1) | $c_{11}$ | $c_{22}$ (m-1) | $c_{21}$ |
|---|---|---|---|---|---|---|---|---|
| Birch (betula) | -0.14 | 7.31 | 0.028 | -3.22 | -0.11 | 0.51 | 0.028 | -2.22 |
| Spruce (picea) | -0.12 | 7.23 | 0.026 | -3.26 | -0.09 | 0.44 | 0.026 | -2.26 |
| Pine (pinus) | -0.12 | 7.02 | 0.025 | -3.25 | -0.09 | 0.32 | 0.025 | -2.25 |

Considering the relative small differences in the parameterization for the tree species and the inherent uncertainty involved in the basic data and used approximation, it might be reasonable just to use one parameterization for all species for a first order of magnitude approach.

## 2.6 Crown cover

Regarding the beneficial effect of forest on the stability of the snowpack, crown cover is the major contributing factor (Gubler and Rychetnik, 1991). The crown cover can be calculated as

$$\mathrm{CC} = \pi\, C_r^2\, N_{ha} \tag{17}$$

where $C_r$ is the maximum crown radius and $N_{ha}$ the number of trees per ha ($10^4$ m$^2$). According to Nagel (2002) (cited in Widlowski and others, 2003) crown radius for birch can be estimated by

$$C_r = 0.1617 + 0.1030\,\mathrm{BHD} \qquad [\mathrm{m}] \tag{18}$$

and similarly for spruce

$$C_r = 0.6122 + 0.0536\,\mathrm{BHD} \qquad [\mathrm{m}]\,. \tag{19}$$

For pine trees, Cermak (2002) (cited in Widlowski and others, 2003) proposed the relation

$$C_r = \sqrt{\frac{0.0067\,\mathrm{BHD}^2 + 0.2126\,\mathrm{BHD}}{\pi}} \qquad [\mathrm{m}] \tag{20}$$

for crown radius at maximum width.

Bauerhansl and others (2010) suggests a critical crown cover of at least 0.5 to have sufficient impact on snowpack stability. This is, however, an on-going research topic, e.g. Teich and others (2016). At this point it is also noteworthy to state that the effective crown cover of birch trees, as for all deciduous trees, is highly reduced during winter.

Figure 6 a) shows examples of the crown diameter for birch, spruce, and pine trees depending on age for appraisement class $H_{40}11$ and Figure 6 b) for crown cover plots.

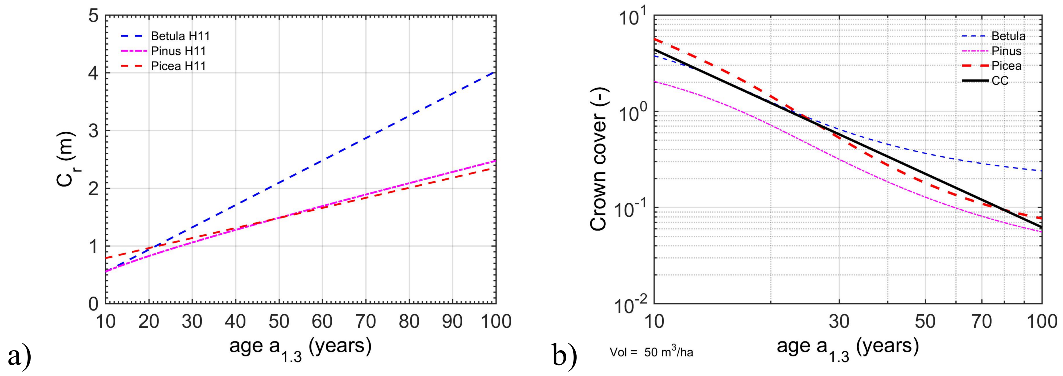


*Figure 6 a) Crown radius of tree versus age for appraisement classes* $H_{40}11$*. b) Crown cover versus age for appraisement classes* $H_{40}12$ *and a timber volume of 50* $m^3$ *per hectare. CC marks a fit for spruce.*

# 3 Effectiveness of forest in a release area

Forest stands have a considerable protective effect against avalanche release due to the support of the snowpack by tree trunks. In this section, some basic requirements on single trees and/or a forest stand are outlined that are needed to fulfill this protective effect; that is firstly to withstand loads due to the snowpack and secondly to contribute to the stabilization of the snowpack against natural avalanche release.

## 3.1 Basic requirements

As mentioned above, for a forest stand to be effective as support for a snowpack the stand needs to have sufficient mechanical stability. In a first approach, this means that a single tree hac sufficient bending strength.

### 3.1.1 Mechanical stability and bending moment

Following Mattheck (2002), the maximum bending stress, $\sigma_{max}$, in a solid tree stem is

$$\sigma_{max} = \frac{32\,M}{\pi d^3}\,, \tag{21}$$

where $M$ is the applied moment and $d$ the stem diameter. The equation can be resolved for the critical diameter

$$d_{cri} = \left(\frac{32\,M}{\pi \sigma_{mor}}\right)^{1/3}\,. \tag{22}$$

where $\sigma_{mor}$ is the bending strength at rupture/the modulus of rupture (MOR). Typical values for the strength of trees are given in Tab. 4.

*Table 4 Strength of trees in MPa for different tree families. The table gives only a rough impression of the strength and its variability depending on species, growth conditions and moisture content. (In the following section, the bold faced values are taken as basis.)*

| spruce | pine | birch | strength | reference |
|---|---|---|---|---|
| 20 | 25 | 25 | compression strength | (Mattheck, 2002) |
| **31** | **39** | **54** | modulus of rupture (MOR) | **(Peltola and others, 1999)** |
| 67 | | | modulus of rupture (MOR) | (Steffenrenm and others, 2007) |
| 32 | 52 | 44 | modulus of rupture (MOR) | (Green and others, 1999) |
| | 38 | | modulus of rupture (MOR) | (Silins and others, 2000) |
| | 38 | | modulus of rupture (MOR) | (Jakubowski and others, 2011) |

Disregarding bottom friction at the time of release, one square meter snowpack on a slope exerts a horizontal force of

$$F_s = \rho\, g\, \mathrm{HS}\, \cos^2\phi \sin\phi\, (1\,\mathrm{m}^2) \tag{23}$$

onto a standing obstacle and the corresponding bending moment is

$$M_s \approx \rho\, g\, \frac{\mathrm{HS}^2}{2} \cos^2\phi\, \sin\phi\, (1\,\mathrm{m}^2)\,. \tag{24}$$

Here, HS is the snow height measured vertically. If one assumes that in a forest with a stand density, $N_{ha}$, a snowpack area of $1/N_{ha}$ is hold in place by a single tree, one obtains the requirement for the minimal tree diameter by using (24)

$$d_{cri} \approx \left( \frac{16\, \rho\, g\, (\mathrm{HS}\, \cos\phi)^2\, (1\,\mathrm{m}^2)}{\pi \sigma_{mor}\, N_{ha}\, 10^{-4}} \sin\phi \right)^{1/3}, \tag{25}$$

or the relation

$$d_{cri} N \propto (\mathrm{HS}\, N_{ha})^{2/3}\,. \tag{26}$$

Figure 7 and 8 depict these relations. The critical values are rough but conservative estimates as the bottom friction of the snowpack is neglected.

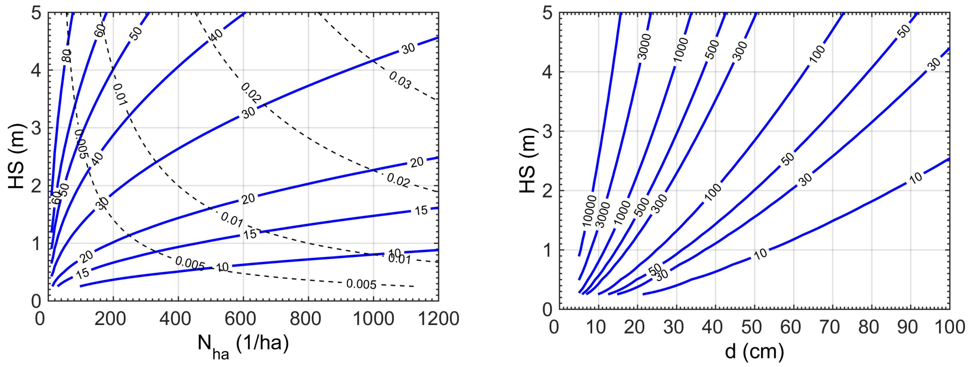


*Figure 7 Minimal required stem diameter $d_{cri}$ (in cm; solid blue lines; left) for a spruce stand according to for Eq. (25) depending on the number of trees, $N_{ha}$, and HS for a slope angle of 35°. The dashed lines depict the corresponding value of $d_{cri}N$ in m$^{-1}$. Minimal required number of trees per hectare depending on diameter, $d_{cri}$, and HS for a slope angle of 35° (right).*

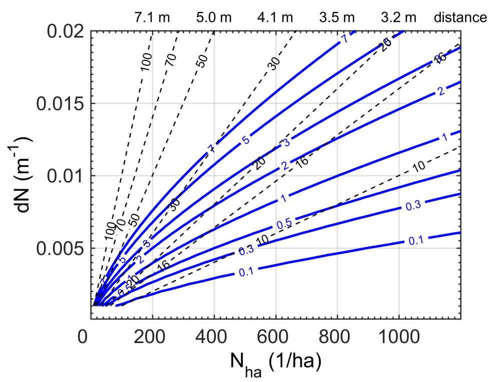


*Figure 8 Minimal required $dN$ factor versus $N_{ha}$ for a given snow depth HS (blue lines; in m) and a slope angle of 35°. In addition the corresponding BHD are shown (in cm; dashed lines). The top axis shows the equivalent distance between trees.*

### 3.1.2 Swiss guidelines approach for a force on a pylon

On the other hand, according to the Swiss guidelines (Margreth, 2007; Ancey and Bain, 2015), the force of the snowpack on a mast like obstacle with diameter, $d$, and vice versa can be computed by

$$F_{SG} = \frac{1}{2}\eta_f \, \rho \, g \, \mathrm{HS}^2 \cos^h(\phi) \, d \, K \, N_g \,, \tag{27}$$

where $\eta_f = 1 + c\,\mathrm{HS}\cos(\phi)/d$, and where $c$ is an empirical gliding factor that ranges from 0.6 (low gliding rate) to 6 (high gliding rate); typically, $c \approx 1.5$. Just regarding the horizontal force, the exponent $h$ is 1 otherwise 0. Haefeli's creep factor $K$ can be given as

$$K = \sin(2\phi)(2.5\,s^3 - 1.86\,s^2 + 1.06\,s + 0.54)\,, \tag{28}$$

with $s = \rho/(1000\ \mathrm{kg\,m^{-3}})$. K ranges typically between 0.5 and 0.9. Haefelis's glide $N_g$ varies from between 1.2 (rough slopes) ad 3.2 (smooth slopes) (cf. Margreth, 2007). Using Eq. (27) and (22) one obtains an approximation for the critical stem diameter for a single tree depending on the snow depth.

$$d_{cri} = \left( \frac{16}{3\,\pi} \frac{\rho \, g \, \eta_{f1} \, \mathrm{HS}_m^3 \cos^h \phi N_g \, K}{\sigma_{mor}} \sin\phi \right)^{1/3} \,, \tag{29}$$

where $\eta_{f1} = 1 + 3/4\, c\,\mathrm{HS}\cos(\phi)/d_{cri}$, which is approximately equal to $\eta_f$. Figure 9 depicts an example for spruce and birch.

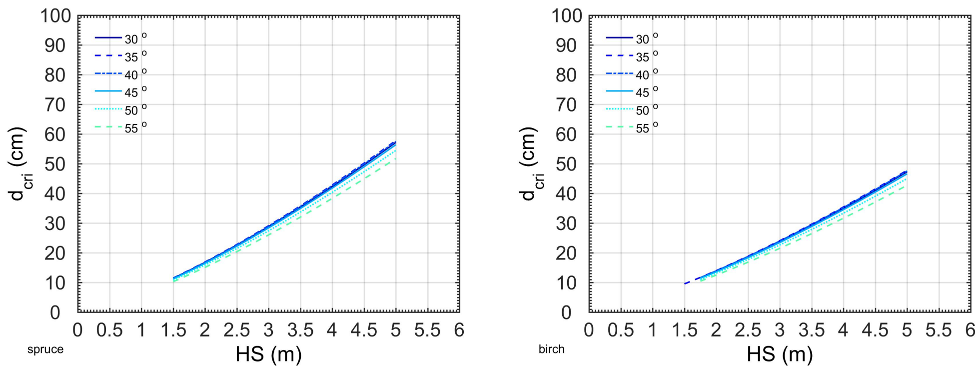


*Figure 9 Critical stem diameter $d_{cri}$ (in cm) for spruce (left panel) and birch (right panel) according to Eq. (29) depending on the snow depth HS for slope angles between 30° and 55°; ($\rho = 250\ \mathrm{kg\,m^{-3}}$, $c = 1.9$ and $N_g = 3.2$).*

Using Eq. (23) and (27), one obtains an approximation for the maximum area a single tree could support and with that an approximation of the required number of trees per ha:

$$a_m \approx \frac{F_{SG}}{F_s} = \frac{1}{2} \frac{\eta_f \text{HS}\, d\, K\, N_g}{\cos(\phi)\sin(\phi)} \tag{30}$$

and

$$N_{ha_{cri}} = 10^4 / a_m \quad [1/\text{ha}]\,. \tag{31}$$

Figure 10 depicts the minimal number, $N_{ha_{cri}}$, of trees per ha for a spruce stand according to for Eq. (31). The decrease of $N_{ha_{cri}}$ with increase HS is attributed to the increase of the zone of influence of the tree on the snowpack. Similar behavior also is assumed by defining the required distance between defense structures (Margreth, 2007). The right panel of the figure shows a plot of the corresponding values of $d_{cri}N$ versus $N_{ha}$.

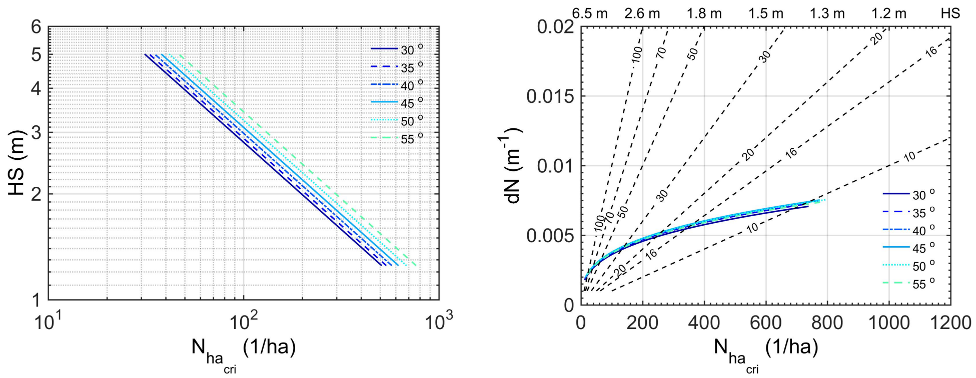


*Figure 10 Minimal number of trees per ha for a spruce stand according to for Eq. (31) to ensure stand stability depending on HS for a slope angles between 30° and 55°;* $\rho = 250\,\text{kg}\,\text{m}^{-3}$*,* $c = 1.9$ *and* $N_g = 3.2$*. The right panel depicts the corresponding values of* $d_{cri}N$ *in m*$^{-1}$ *versus* $N_{ha}$*. As reference the commensurating BHD values are shown (dashed lines) as well as the commensurating HS as top axis.*

## 3.2 Simple snowpack stability aspects

A further requisition on a forest stand is to ensure sufficient support of the snowpack against natural avalanche release. In this context it is necessary to consider snowpack stability and the support due to tree trunks. To this end, a simple model for the release of a (infinite) slab avalanche is considered using a Mohr-Coulomb stability criteria that accounts for the support of the slab due to trees.

### 3.2.1 Simple avalanche slab model

In this way, one obtains the following performance function, where $G < 0$ implies failure

$$G = \underbrace{-\rho\, g\, \mathrm{HS} \cos\phi \sin\phi}_{-L} + \underbrace{(C + \mu_s\, \rho\, g\, \mathrm{HS} \cos^2\phi) + \frac{N_{ha}}{10^4}\frac{1}{2}\eta_f\, \rho\, g\, \mathrm{HS}^2\, d_t\, K\, N_g}_{R} \quad (32)$$

or in non-dimensionalized form

$$G_{nd} = -1 + \left( \underbrace{\frac{C}{g\, \rho\, \mathrm{HS} \cos\phi \sin\phi}}_{\mathcal{O}\approx 0.1-1} + \underbrace{\mu_s \cot\phi}_{\mathcal{O}\approx 0.3-1} \right) + \underbrace{\frac{N_{ha}}{10^4}\frac{1}{2}\eta_f \frac{\mathrm{HS}\, d_t\, K\, N_g}{\cos\phi \sin\phi}}_{R_{FS}} . \quad (33)$$

$L$ marks the driving force and $R$ the resisting one. Especially, $R_{FS}$ marks support due to trees. The values under the underbraces in (33) give the expected order of magnitude of the respective terms for using $C = 0.5$ kPa and $\mu_s = 0.4$, which are proposed values. For Example, Salm and others (1990) suggest a order

$$\frac{C}{\rho_s\, g\, \mathrm{HS} \cos\phi} \sim 0.291 . \quad (34)$$

The last term on the right hand side of (32) marked $R_{FS}$ is the contribution of trees to the stabilization of the snowpack. Here, only the possibility of a natural release is considered. To obtain sufficient additional support due to a forest stand, this term probably needs to be in the order of $\mathcal{O} \approx 0.3$ depending on the slope angle, which gives some restriction to the stand parameters $d_{1.3}$ and $N_{ha}$:

$$\mathcal{O}\left( \frac{d_t\, N_{ha}}{10^4}\frac{1}{2}\eta_f \frac{\mathrm{HS}\, K\, N_g}{\cos\phi \sin\phi} \right) \approx 0.3; \quad (35)$$

Just considering the simple release model with the Mohr-Coulomb stability criteria one can calculate the stability deficiency as shown in Figure 11. This deficit needs to be accounted for by the forest stand.

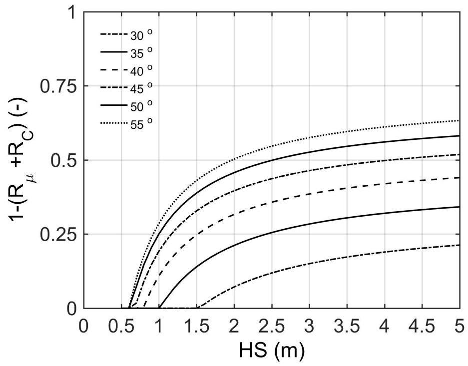


*Figure 11 Stability deficiency of a snowpack just considering a Mohr-Coulomb model with* $\mu = 0.4$ *and* $C = 0.5$ *kPa.*

### 3.2.2 Probabilistic consideration on the required order of magnitude of the mechanical stabilization effect of a forest stand

To give further constraints to the required contribution of a forest stand, a probabilistic approach to equation (33) is used:

$$G_{nd} = -1 + \underbrace{\frac{C}{g\,\rho\,\mathrm{HS}\cos\phi\sin\phi} + \mu_s\cot\phi}_{R_s} + \underbrace{\frac{N_{ha}}{10^4}\frac{1}{2}\eta_f\,\frac{\mathrm{HS}\,d_t\,K\,N_g}{\cos\phi\sin\phi}}_{R_{FS}}\,. \tag{36}$$

or rewritten as

$$G_{nd} = -1 + R_s + R_{FS}\,. \tag{37}$$

**Baseline probability** Now, if one assumes that the avalanche return period needs to be longer than 10 to 100 years in presently forested terrain otherwise a forest would not have had the chance to establish. This suggests that the annual avalanche probability without forest should be less than 0.1 or 0.01. Assuming that the probability of an avalanche release is normal distributed, this implies that

$$p_r = P\left\{G_{nd}(1, R_s) < 0\right\} \approx 0.01\text{–}0.1\,. \tag{38}$$

Further, writing (38) as standard normal distribution

$$p_r = \Phi(-\beta_s)\,, \tag{39}$$

where

$$\beta_r = \frac{\mu_{R_s} - 1}{\sigma_s}\,. \tag{40}$$

This gives

$$\mu_{R_s} = 1 - \beta_r\,\sigma_s \tag{41}$$

where $\mu_{R_s}$ is the expected mean of the snowpack strength and $\sigma_s$ the is its standard deviation. With the given probability range 0.01 – 0.1 assumed above, $\beta_r$ ranges between 2.33 and 1.28. Furthermore, assuming $\sigma_s = 0.1\,\mu_{R_s}$, one obtains

$$\mu_{R_s} = \frac{1}{1 - 0.1\beta_r}\,. \tag{42}$$

and using the estimated values for $\beta_r$, it follows

$$\mu_{R_s} \approx 1.15 - 1.3\,. \tag{43}$$

Now, it is reasonable to assume that the release probability assumed in (38) increases with increasing slope angle. Therefore, the relation

$$p_r(\phi) = 0.01 + 0.09\left(\frac{\tan(\phi) - \tan(30)}{\tan(55) - \tan(30)}\right) \tag{44}$$

will be taken as basis later on. In Fig. 12, it is marked as $R_m$.

**Required safety** Regarding the required safety, the indication maps focus on an annual avalanche probability of less than 1/1000. In a first conservative approach this gives a constrain to an annual avalanche releases probability that includes the effect of forest,

$$p_{rf} = P\left\{G_{nd}(1, R_s, R_{FS}) < 0\right\} \approx 0.001\,. \tag{45}$$

Again a standard normal distribution is considered

$$p_{rf} = \Phi(-\beta_{rf}) \,, \tag{46}$$

where

$$\beta_{rf} = \frac{\mu_{R_s} + \mu_{R_{FS}-1}}{\sqrt{\sigma_S^2 + \sigma_{FS}^2}} \,.. \tag{47}$$

For the required safety, this implies $\beta_{rf} \approx 3.09$ and using

$$\mu_{FS} \approx 1 - \mu_{R_s} + \beta_{rf}\sqrt{\sigma_S^2 + \sigma_{FS}^2} \,, \tag{48}$$

this gives an required contribution of the forest of the order

$$\mathcal{O}(\mu_{R_{FS}}) \approx 0.1 – 0.21 \,, \tag{49}$$

depending on the assumed initial return period and assuming $\mathrm{O}(\sigma_S^2) \approx \mathcal{O}(\sigma_{FS}^2)$.

**Proposed minimal mechanical contribution due to forest stands** Based on the results of Paragraph 3.2.2, the following relation for a minimal contribution of a forest stand as function of the slope angle is proposed

$$R_{fs} = 0.075 \left(1 + \frac{\tan(\phi) - \tan(30)}{\tan(55) - \tan(30)}\right) . \tag{50}$$

With this proposal in mind, Figure 12 shows the expected avalanche probability for different scenarios:

- constant annual avalanche release probability of 0.1, no forest ($R_T = 10$ years);
- constant annual avalanche release probability of 0.01, no forest ($R_T = 100$ years);
- avalanche release probability depending on the slope angle according to Eq. (44), no forest ($R_m$);
- like the first but accounting for a forest stand according to Eq. (50) ($f_{10}$);

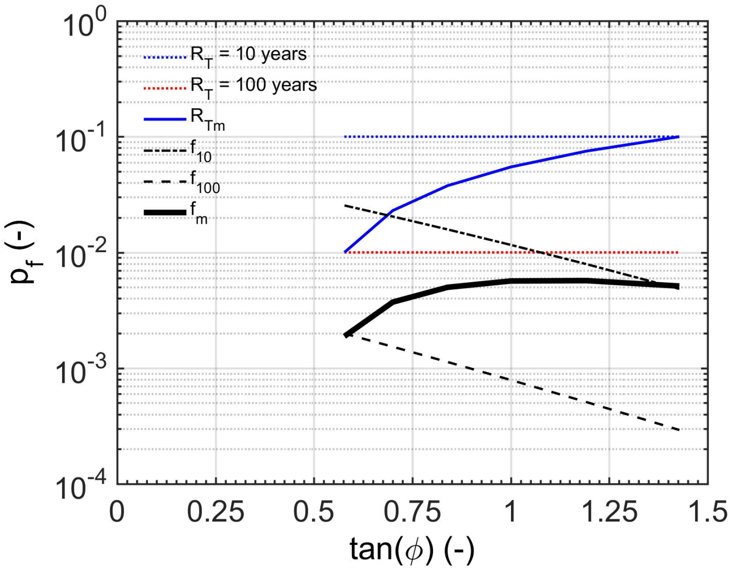


*Figure 12 Expected avalanche probability for different scenarios.*

- like the second but accounting for a forest stand according to Eq. (50) ($f_{100}$);
- like the third but accounting for a forest stand according to Eq. (50) ($f_m$);

The proposed values for the forest contributions suggests that just regarding the mechanical stabilization the release probability does not meet the requirements (Figure 12 line $f_m$). However, in addition one can expect a reduction of the release probability due to the change in snowpack conditions in a forest stand, which is not accounted for yet.

The propose requirements in Eq. (50) give requisitions on minimal forest parameters depending on the slope:

$$R_{fs}(\phi) = \frac{1}{2}\frac{N_{ha}\, d_t}{10^4}\frac{\eta_f\, \mathrm{HS}\, K\, N_g}{\cos\phi \sin\phi} \tag{51}$$

In addition, Eqs. (22) and (27) provide criteria for the stability of a single tree depending on the slope angle and expected maximum snow depth $\mathrm{HS}_m$

$$d_{cri} \approx \left(\frac{16}{3\,\pi}\frac{\rho\, g\, \eta_{f1}\, \mathrm{HS}_m^3 \cos^h \phi N_g\, K}{\sigma_{mor}}\, \sin\phi\right)^{1/3}, \tag{52}$$

and (22) requirements for a stand

$$d_{cs} \approx \left( \frac{16\, \rho\, g\, \mathrm{HS}_m^2\, \cos\phi\, (1\,\mathrm{m}^2)}{\pi \sigma_{mor} N_{ha}\, 10^{-4}}\, \sin\phi \right)^{1/3} . \tag{53}$$

The combination of both provide restriction on the minimal stem diameter to ensure forest stability, that is

$$d_{cmin} = \max(d_{cri}, d_{cs}) \tag{54}$$

Finally, combing all requirements, one obtains constraints for the forest stand parameter $dN$ and $N_{ha}$ as depict in Figure 13.

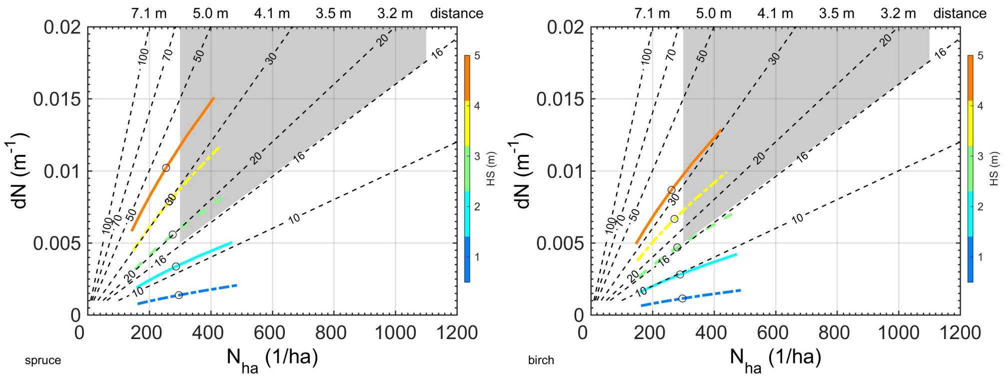


*Figure 13 $dN$ versus number of trees per ha, $N_{ha}$ depending on HS for slope angles between 30° and 55° to obtain a forest contribution according to condition (50) for a spruce stand (left panel) and birch stand (right panel) to the stabilization of the snowpack. Snowpack parameter: $\overline{\rho}_s = 250\, kg\, m^{-3}$; $c = 1.5$ and $N_g = 1.2$. As reference the commensurating BHD (in cm) values are shown (dashed black lines). Circles mark the numbers for a 40° slope. The grey shaded shows the range specified by (Meyer-Grass and Schneebeli, 1992, see below).*

With that it is also possible to calculate the required forest stand parameter $dN$ as function of the slope angle shown in Figure 14 for spruce and birch stands. For comparison also some proposed requirements given in the literature are shown (see discussion in Section 3.3 below).

## 3.3 Proposed requirements on the forest stand given in the literature

For comparison, this section provides a brief review on proposed requirements on forest stands in the literature.

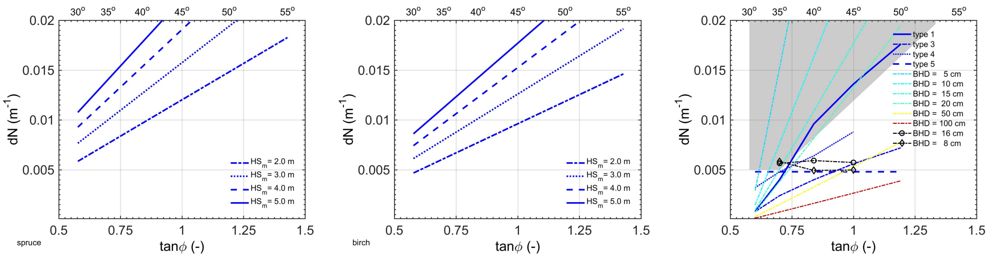


*Figure 14 Required $dN$ versus $\tan\phi$ with HS as parameter. For comparison, right panel shows the criteria according to Meyer-Grass and Schneebeli (1992), Ishikawa and others (1969), and Viglietti and others (2010) in a similar presentation.*

**Salm (1979)** Based on similar consideration as described in Section 3.1.2, Salm (1979) proposed the following minimal number of tree per ha (plan view)

$$N_{ha} = \frac{K}{R}\frac{10^4}{\cos\phi}\,. \tag{55}$$

where

$$K = \rho\, g\, D(\sin\phi - f\cos\phi)\,, \tag{56}$$

$$R = F\, D = \frac{2\pi\,(1+\nu)}{1+2(1+\nu)}\,\frac{\rho\, g\, D^3\,(1+2\,n)\sin\phi}{\ln(2x_b/d_{1.3})} \tag{57}$$

and

$$x_b = \frac{1}{\pi\,(1+\nu)\cos(\phi)}\,\frac{F}{\rho\, g\, D}\,. \tag{58}$$

Here, the following notation is used

- $D$ is the snow thickness (normal to the surface);
- $\rho$ the density of the snowpack;
- $f$ is the coefficient of friction ($\approx 0.5$);
- $\nu$ is the viscous analogue of Poisson's ration ($0 \le \nu \le 0.5$);
- $n$ is the relative glide velocity ($\approx (N_g^2 - 1)/3$ );

- $x_b$ is the back-pressure zone in upslope direction.

Figure 15 plots the minimal number of trees required according to (55). The increase in minimal number of trees with decreasing snow thickness is caused by a decreasing zone of influence of a tree with decreasing $D$. In this consideration no regards to the stability of the trees is taken.

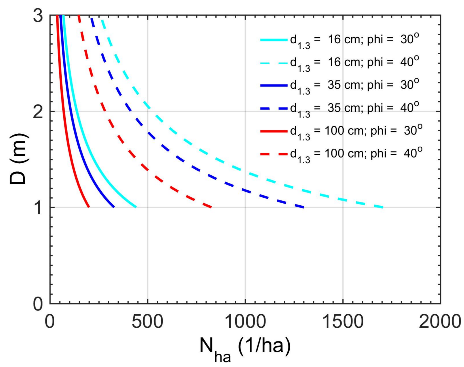


*Figure 15 Minimal number of trees per ha plan view required to stabilize the snow cover depending on the thickness of the snow cover, $D$, according to Salm (1979) with $f = 0.5$, $\nu = 0.2$ and $N_g = 2$.*

**Ishikawa and others (1969)** Ishikawa and others (1969) proposed a relationship between the required number of tree per ha and the slope angle for different tree diameters. This relationship can be expresses in the following form for the parameter $dN_{cri}$

$$d\,N_{cri} = 1.25\,\frac{\phi - 30°}{d_{1.3}\cos\phi}\,. \tag{59}$$

**Meyer-Grass and Schneebeli (1992)** Meyer-Grass and Schneebeli (1992) proposed the following minimal requirements.

*Table 5 Required number of conifer trees per ha (BHD $>$ 16 cm) depending on the slope angle to prevent avalanche release according to Meyer-Grass and Schneebeli (1992). Forest types are detailed in the paper.*

| slope [°] | Number of trees per ha (BHD $>$ 16 cm) forest type | | | |
|---|---|---|---|---|
| | 1 | 3 | 4 | 5 |
| 30 | 50 | 50 | 200 | 300 |
| 35 | 250 | 150 | 300 | 300 |
| 40 | 600 | 250 | 400 | 300 |
| 45 | 850 | 350 | 550 | 300 |
| 50 | 1100 | 450 | - | 300 |

**Viglietti and others (2010)** Viglietti and others (2010) investigated the structural characteristics of the forest outside the release zone that is the mean values of stem density and crown cover depending on the slope angle.

*Table 6 Structural characteristics of the forest outside the release zone: mean values of stem density and crown cover depending on slope angle. n means number of plots. (Viglietti and others, 2010).*

| slope [°] | $<$ 35° | 35°–40° | $>$ 40° |
|---|---|---|---|
| Number of trees per ha (BHD $>$ 8 cm) | 728 | 616 | 622 |
| Number of trees per ha (BHD $>$ 16 cm) | 353 | 370 | 358 |
| Crown cover | 0.49 | 0.66 | 0.46 |
| n | 3 | 6 | 3 |

## 3.4 Summary

The minimal forest parameters defined in Tab. 5 and Tab. 6 may be translate in a relation of the forest structure parameter $dN$ and the sinus of the slope angle, $\sin\phi$. The grey shaded area in Figure 16 depicts the minimal requirements according to Meyer-Grass and Schneebeli (1992). Similarly, these requirements can be presented as functions of $dN$ and $N_{ha}$ as shown in Figure 17.

Keeping the mechanical and geometrical consideration mentioned above in mind, following forest parameter might be considered as a minimal (conservative) requirement:

- $N_{ha} \geq 300$, which ensures that the gap length between trees is less than about 6 m.
- $dN \geq 0.01$ m$^{-1}$, which ensures for conifers a crown cover of more than 0.5,

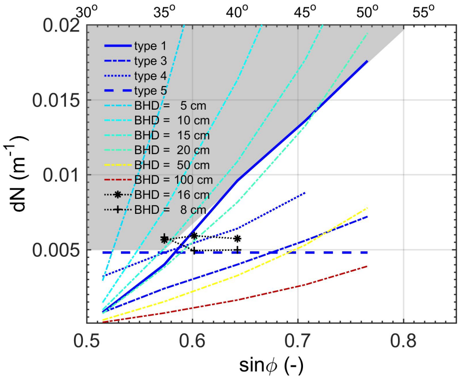


*Figure 16 Minimal required $dN$ factor versus $\sin\phi$ according to the requirements from Meyer-Grass and Schneebeli (1992) given in Tab. 5 and according to Ishikawa and others (1969) given in (59) for various BHD. Include are also the data from Viglietti and others (2010). According to Meyer-Grass and Schneebeli (1992), the grey shaded area depicts the range that could be regarded sufficient for BHD $> 16$ cm.*

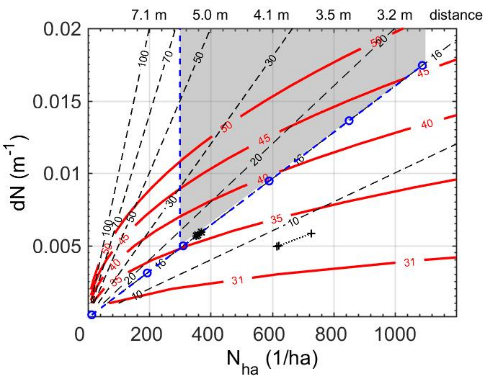


*Figure 17 Minimal required $dN$ factor versus $N_{ha}$ according to the requirements from Meyer-Grass and Schneebeli (1992) given in Tab. 5 and according to Ishikawa and others (1969) given in (59) for various BHD (cm) (colored lines). Included are also the data from Viglietti and others (2010) (black markers). According to Meyer-Grass and Schneebeli (1992), the grey shaded area depicts the range that could be regarded sufficient for BHD $> 16$ cm. The top axis shows the equivalent distance between trees.*

if $N_{ha} \geq 300$ (see Figure 19). In the case of deciduous trees, this probably ensures only a crown cover of about 0.2 in winter.

- $dN \geq 0.01$ m$^{-1}$, ensures mostly a sufficient stability of the stand against typical snow pressure loads.
- $dN \geq 0.01$ m$^{-1}$, ensures probably that a forest stand can contribute to least about 10% to the stabilization of the snowpack.

However, it should be note that the requirement $dN \geq 0.01$ m$^{-1}$ is rather stringent considering, e.g., typical Norwegian forest stands. Figure 18 gives an impression of the relation between stand volume and the number, $N_{ha}$, of trees per ha for the requirement $dN = 0.005$ m$^{-1}$ and $dN = 0.01$ m$^{-1}$.

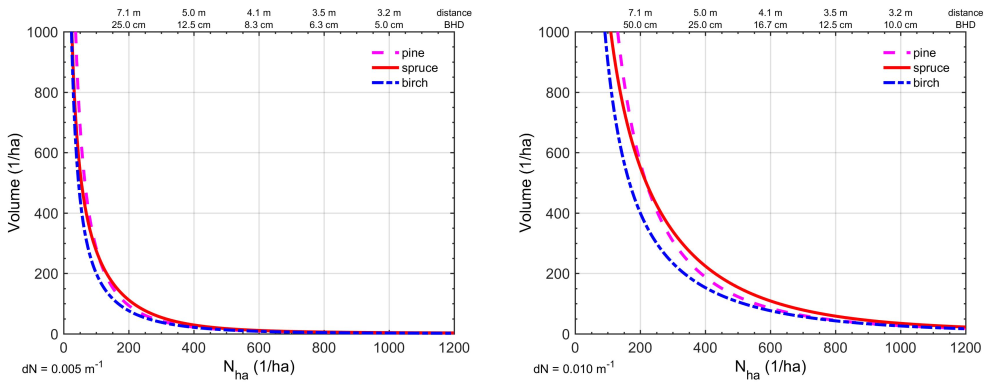


*Figure 18 Stand volume versus $N_{ha}$ for $dN = 0.005$ m$^{-1}$ (left) and $dN = 0.01$ m$^{-1}$ (right). The top axis shows the respective BHD and the corresponding mean distance between trees.*

Figure 19 gives an impression how crown cover is related to the given forest parameters $dN$ and $N_{ha}$. To this end, a effective winter crown cover for birch of 20% is assumed.

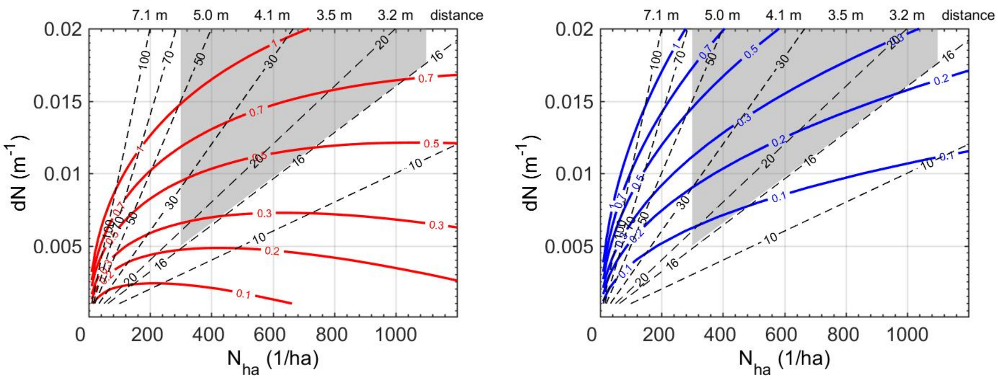


*Figure 19 Crown-cover on a flat as function of $N_{ha}$ and $dN$ for spruce (left panel; red solid lines) and birch (right panel; blue solid lines). For birch an effective crown cover of 0.2 in comparison to the summer crown cover was assumed. In addition the corresponding BHD are shown (in cm; dashed lines). According to Meyer-Grass and Schneebeli (1992), the grey shaded area depicts the range that could be regarded sufficient for BHD $> 16$ cm. The top axis shows the equivalent distance between trees.*

## 3.5 Proposed parameterization

This section describes the presently-proposed parameterization of the required forest stand parameters given above. Thereby, some of the requisition are slightly relaxed.

The justification of these relaxations needs to be verified in future work. The parameterization is based on simple fitting relations to simplify the calculation procedure in a GIS-tool. Here, we only distinguish between birch and spruce as the parameters for pine are very similar to those for spruce.

**Stability of single trees and of a forest stand** Regarding the stability of single tree, the following parameterization for the a critical stem diameter, $d_{cri}$, (see Eq. (52)) is used:

$$d_{cri} \approx \max(c_{dc2}\,\mathrm{HS}_{max} + c_{dc1}, d_{min}) \quad [\mathrm{m}], , \tag{60}$$

where, $\mathrm{HS}_{max}$ is the expected maximum snow depth. Considering the stability of the stand

$$d_{cs} \geq c_{cs} HS^{2/3}\, N_{ha}.^{-1/3} \quad [\mathrm{m}] \tag{61}$$

needs to be fulfilled. $N_{ha}$ is given in 1/ha. As mentioned above, the combined stability requirements gives $d_{cmin} = \max(d_{cri}, d_{cs})$. Table 7 gives the species specific constants.

*Table 7 Tree species specific constants for $d_{cri}$*

| species | $c_{dc2}$ (-) | $c_{dc1}$ (m) | $d_{min}$ (m) | $c_{cs}$ ($\mathrm{m}^{1/3}\ \mathrm{ha}^{1/3}$) |
|---|---|---|---|---|
| birch | 0.8 | -0.06 | 0.1 | 1 |
| spruce | 0.10 | -0.09 | 0.12 | 1.25 |

**Minimal mean forest stand density** Generally, the increase in the support due to trees with increasing snow depth is due to increase of the area of influence. Similar effects are known from defence structures. Therefore, most critical might actually be snow depths less than about 1 to 2 meter. To ensure minimal distance distance between trees the following critical stand density relation is proposed:

$$N_{ha_{cri}} \approx 160 + 400\frac{\tan(\phi) - \tan(30)}{\tan(55) - \tan(30)} \quad [1/\mathrm{ha}] \tag{62}$$

Figure 20 show the corresponding mean distance between trees.

**Stability of the forest stand** Finally, combing all the requirements previously described, one can derive the following parameterization for the stand parameter $dN$:

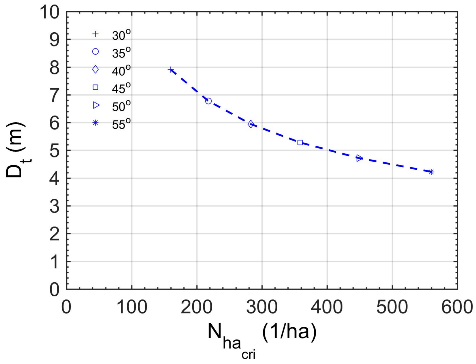


*Figure 20 Calculated mean distance between trees versus $N_{ha_{cri}}$ according Eq. (62)*

$$dN \approx c_{nd2}(\mathrm{HS}\,N_{ha})^{2/3} + c_{nd1}; \tag{63}$$

presupposed that

$$N_{ha} \geq N_{ha_{cri}} \quad \text{and } dN \geq d_{cm}\,N_{ha}\,. \tag{64}$$

where $d_{cm}$ is given by (54) and $N_{ha}$ is given in 1/ha. Table 8 gives the species specific constants.

*Table 8 Tree species specific constants for $dN$ parameterization (Eq. 63).*

| species | $c_{nd2}$ ($\mathrm{m}^{1/3}\,\mathrm{ha}^{-2/3}$) | $c_{nd1}$ (m) |
|---|---|---|
| birch | 1E-4 | -5.9E-5 |
| spruce | 1.2E-4 | -7E-5 |

The proposed criteria for $dN$ versus $N_{ha}$ depending on HS and slope angles are visualized in Figure 21. The red shaded area shows the whole range that might be regarded as the range in which forest provides a considerable contributes to the snowpack stabilization. For comparison, the underlying grey-shaded area depicts the proposed range according to Meyer-Grass and Schneebeli (1992). The red contour lines show examples for HS =3, 4, and 5 m and depending on slope angle. In each case, the contour line provides the lower left boundary.

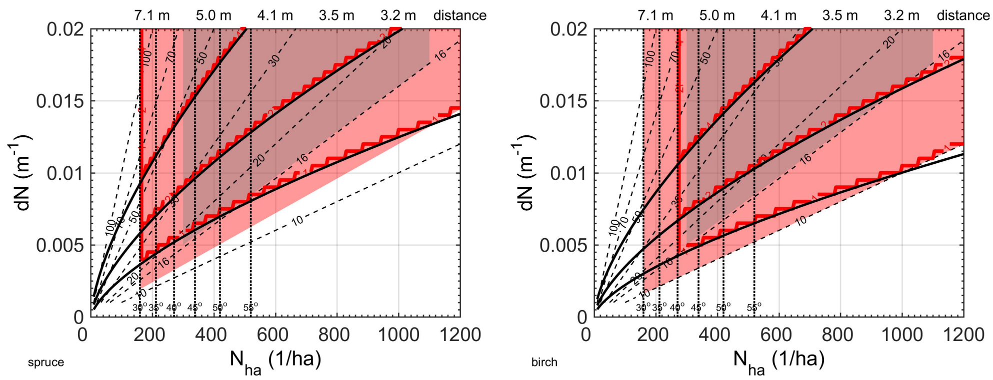


*Figure 21 Proposed criteria for $dN$ versus $N_{ha}$ depending on HS and for slope angles between 30° and 55° to obtain a forest contribution to the stabilization of the snowpack according to condition (51) for a spruce stand (left panel ) and a birch stand (right panel). The red shaded area shows the whole range in which forest provides a considerable contributes to the snowpack stabilization. The contour lines show examples for HS =1, 2, and 4 m and a slope angle of 30° and 40°, respectively. snowpack parameter: $\overline{\rho}_s = 250$ kg m-3; $c = 1.5$ and $N_g = 1.2$). As reference the commensurating BHD (in cm) values are shown (dashed black lines), $N_{ha_{cri}}$ as function of the slope angle black dotted line, and black lines follow (63). According to Meyer-Grass and Schneebeli (1992), the underlying grey-shaded area depicts the range that could be regarded sufficient for BHD $> 16$ cm.*

# 4 Example of forest parameter maps

The parameterization as introduced in Section 3.5 can be implemented in an ArcGis-tool. To this end the following parameter are used:

- SAT-SKOG
  - VUPRHA
  - AGE
  - BONITET
  - TRESLAG
- terrain model (DTM, 10×10 m) and thereof derived slope angles.
- mean annual maximum snow height $HS_m$ provide by seNorge (seNorge.no, 2016); at present, 2.2 $HS_m$ is used as a proxy for the expected maximum snow height with an approximated return period of 100 years.

Figure 22 shows the modular concept of the forest classification tool.

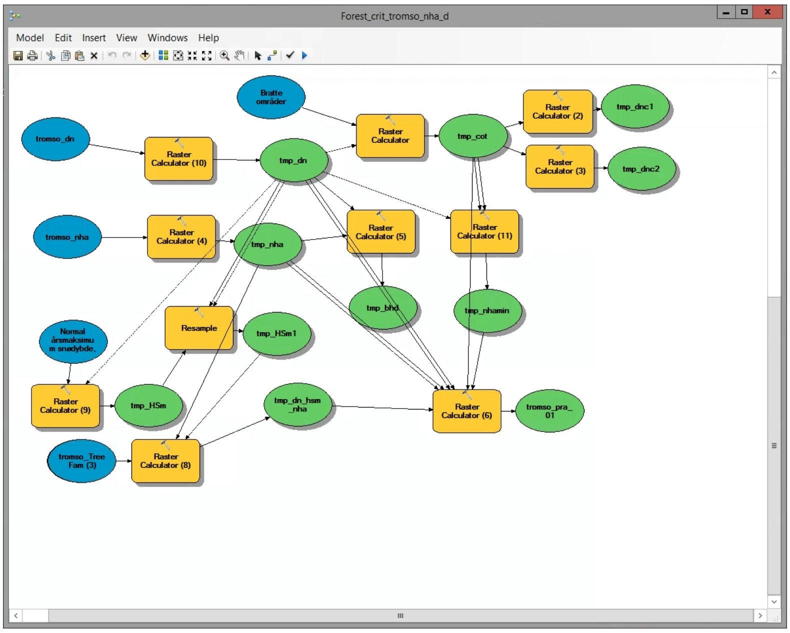


*Figure 22 Concept of the ArcGis-tool for forest stand classification*

Figure 23 shows an example of $dN$ and the corresponding forest classification. At present the forest classification follows the schema given in Tab. 9.

*Table 9 Forest classification scheme*

| classification | description |
| --- | --- |
| -1 | slope angle $< 30°$ and forest stand not classified |
| 0 | slope angle $\geq 30$ ° and a sufficient forest stand |
| 1 | slope angle $\geq 30$ ° and an insufficient forest stand–**possible avalanche release area** |

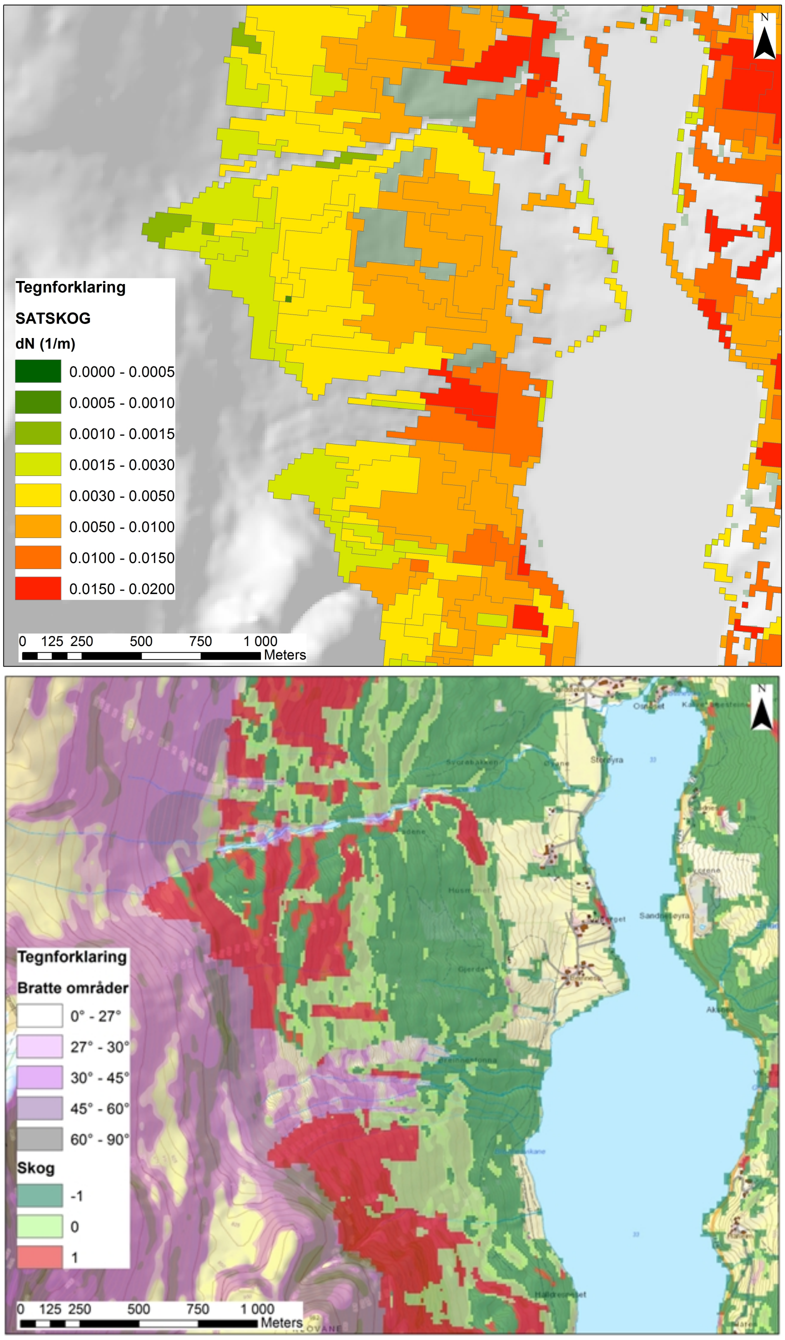


*Figure 23 Example of $dN$ calculations (top) and the corresponding forest classification (bottom).*

# 5 Simple dynamic aspects of forests avalanche interaction

This sections provides some brief considerations on the effect of forests on the avalanche flow dynamics with regard to stand parameters derived from SAT-SKOG.

To this end, using a simple avalanche block model and the ansatz for the force onto a tree given in Eq. (10), one can derive estimates for critical forest parameters in the case of an avalanche; critical in the sense that trees start to break. In this brief assessment, only the flowing part of an avalanche is consider. Extensive powder part may case more damage due to large level arms and therefore larger moments. The most simple avalanche block model is probably the PCM-model (Perla and others, 1980). It can be written as

$$\frac{dU^2}{2ds} = g\ \sin\phi - \left(\mu\, g\ \cos\phi + a_2\, U^2 + 10^{-4}\, d_t\, N_{ha}\, C_D\, \frac{U^2}{2}\right), \tag{65}$$

where $U$ is the avalanche velocity, $s$ the distance along the path, $\phi$ the slope angle, $g$ the gravitational acceleration and $\mu$ and $a_2 (= D/M)$ are the frictional parameters of the PCM model. The lest term on the right hand side is the contribution due to the forest, where $C_D$ is the drag factor, $d_t$ the tree diameter in m and $10^{-4}N_{ha}$ the number of trees per square meter. In steady state (i.e. $\frac{dU^2}{2ds} = 0$), one obtains a relation for the maximum velocity

$$U_{max} = \sqrt{\frac{g\,(\sin\phi - \mu\ \cos\phi)}{a_2 + 10^{-4}\, d_t\, N_{ha}\, C_D/2}}\,. \tag{66}$$

At the same time the force onto a tree is

$$F_{tree} = \rho\, C_D\, d_t\, h_a \frac{U^2}{2}\,, \tag{67}$$

where $h_a$ is the flow height and the moment is

$$M \sim F\, h_a \cos\phi\,. \tag{68}$$

Recalling that the critical diameter for a tree is given by (Eq. 22)

$$d_{cri} = \left(\frac{32\, c_1\, F\, h_a\ \cos\phi}{\pi\, \sigma_{mor}}\right)^{1/3}\,, \tag{69}$$

where $\sigma_{mor}$ is the modulus of rupture (fracture strength) and $c_1$ a factor accounting for the length of the level arm. It is now possible to calculate iteratively the critical forest parameters depending on the slope angle. Figure 24 gives a brief overview. In this case, $\mu = 0.25$, $a_2 = 0.001\,\mathrm{m}^{-1}$, $h_a = 2\,\mathrm{m}$; $\rho = 200\,\mathrm{kg\,m}^{-3}$ and $\sigma_{mor} = 31\,\mathrm{MPa}$ (spruce) are assumed. $c_1$ is set to 1.5 to take some snow on the ground into account and $C_D = 2$ is used.

For example, on a 30° slope with 100 trees spruce per ha the critical diameter $d_{cri} \approx 44\,\mathrm{cm}$ with an avalanche velocity at steady state of $U_{max} \approx 16\,\mathrm{m\,s}^{-1}$might be expected. The corresponding critical forest parameters are $d_{cri}\,N \approx 0.0044\,\mathrm{m}^{-1}$ and volume per ha of around $210\,\mathrm{m}^3$. The respective values for a birch stand are $d_{cri} \approx 36\,\mathrm{cm}$, $U_{max} \approx 16\,\mathrm{m\,s}^{-1}$, $d_{cri}\,N \approx 0.0036\,\mathrm{m}^{-1}$ and volume per ha around $141\,\mathrm{m}^3$.

Figures 25 and 26 give some ideas about mutual interaction between a birch forest and an avalanche. Figure 25 shows the forest parameters derived from SAT-SKOG data and Figure 26 give impression of the area before, during and after the event.

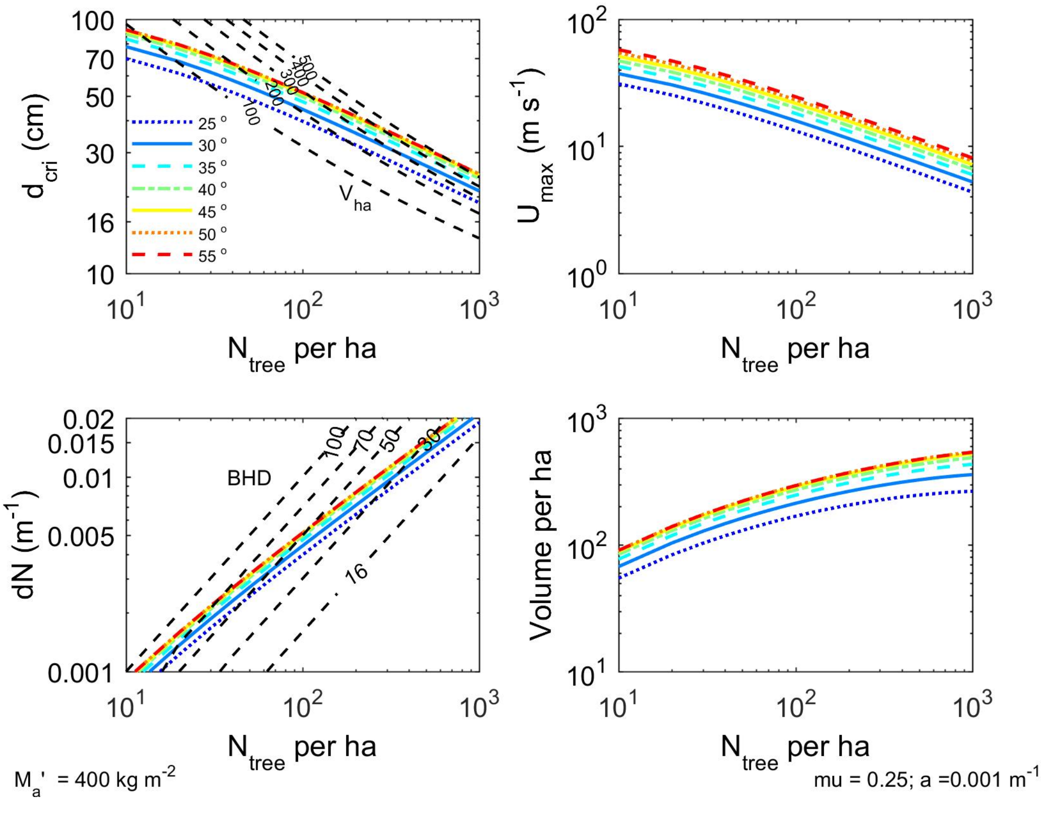


*Figure 24 Relations between stand density (spruce) and critical avalanche impact parameter.*

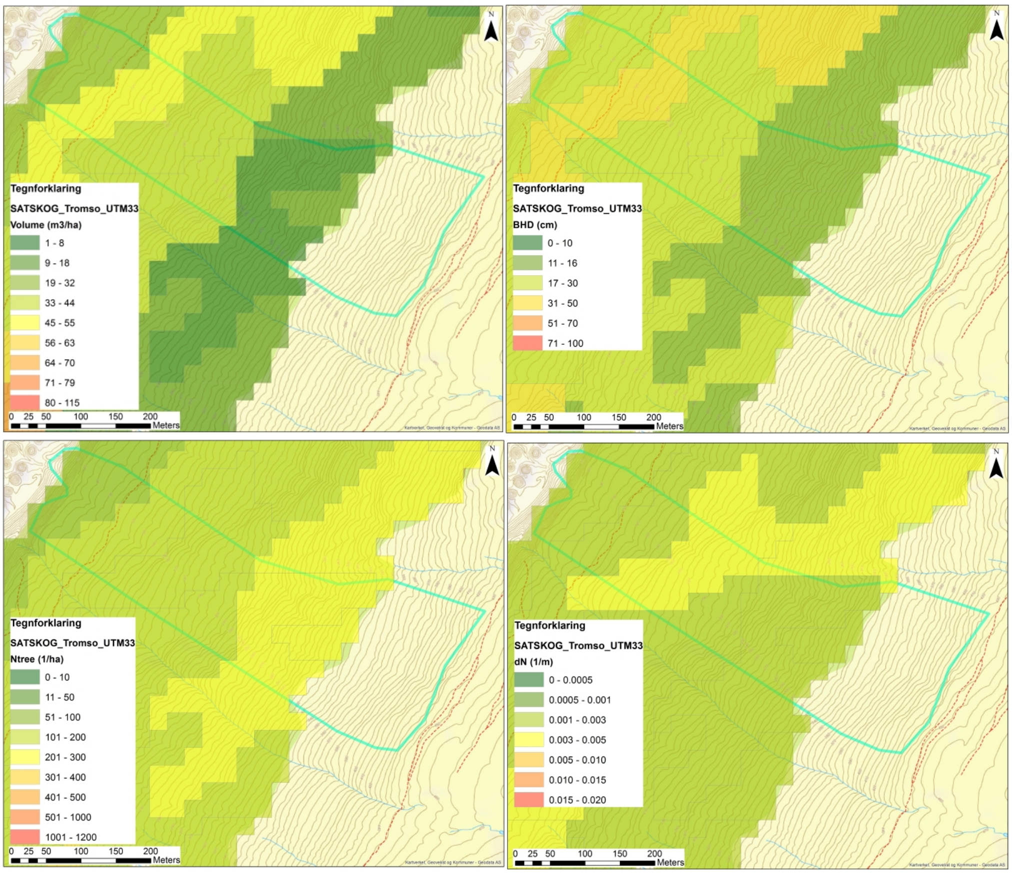


*Figure 25 Avalanche through a birch forest in Tromsø-Reinen on 2013-04-02. The outline depicts the impacted area. Forest parameters are derived from SAT-SKOG: Volume per ha ($m^3$; top left); breast height diameter, BHD, (cm; top right); Number of trees per ha (bottom left); Parameter $dN$ ($m^{-1}$; bottom right);. parameter.*

*Figure 26 Avalanche through a birch forest (Tromsø-Reinen 2013-04-02); snapshot of the event (top), forest some time before the event (bottom left) and shortly after the event (bottom right). (photos anonymous)*

A first adaption of the parameters of commonly used block models might be given by:

**PCM-Model type models** As the PCM model does not directly account for the flow height the adaption just involves an additive term in the retarding acceleration.

$$a_{ret} = \mu\, g\, \cos\phi + \left(\frac{D}{M} + \frac{d_t\, N\, C_D(U)}{2}\right) U^2 \tag{70}$$

**VS-Model type models** With respect to a Voellmy-type models one may think to adapt the turbulent friction parameter:

$$\xi_f = \frac{2g}{C_D\, dN\, h_a} \tag{71}$$

where $C_D$ is the drag factor, $h_a$ the flow height of the avalanche and $g$ the gravitational acceleration. Usually one is forced to assume a typical flow height to ensure a constant friction parameter. For Example, assuming $C_D \approx 2$ and $h_a \approx 2$ m, a $dN$ of $0.01$ m$^{-1}$ corresponds to a $\xi \approx 490$ m s$^{-2}$.

# 6 Concluding remarks

It is widely accepted that a dense forest has a protective effect against avalanche release. However, there are is no universal consensus on the requirements on a forest stand as a protective forest.

Generally, trees in a forest can only support a cohesive snowpack. As soon as snowpack looses its bindings (e.g. due to very high water content) or the snowpack is built up of low cohesive snow (e.g. Wildschnee–diamond snow or champagne powder) a forest loses its protective effect. In rare cases avalanche have released in and run through mature forests under this kind of conditions, e.g. (Hess, 1931).

Furthermore, one has to keep in mind that only healthy forest can keep its protective function. This requires a continues fostering of protective forests.

This technical note describes a first approach to classify forest stands in Norway in respect to their protective effect against natural avalanche release based on SAT-SKOG data (Sat-Skog, 2016). A parameterization of the required forest stand parameters are given, whereby an overall annual avalanche probability of 1/1000 is kept in mind. This parameterization needs to be verified in future work. Improvements might by obtained by using to more sophisticated forest model and allowing for a more diversified forest representation, which is beyond the scope of the present work.

In addition, the dynamic effect of a forest stand is briefly discussed. This discussion is meanly thought to give a first impression of the effect of a forest stand with a given stand parameter $dN$.

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# Kontroll- og referanseside / Review and reference page

| **Dokumentinformasjon/*Document information*** | | |
|---|---|---|
| **Dokumenttittel/*Document title***<br>Forest cover within *Nye aktsomhetskart snøskred i Norge* (NAKSIN) | | **Dokumentnr./*Document no.***<br>20150457-04-TN |
| **Dokumenttype/*Type of document***<br>Teknisk notat / *Technical note* | **Oppdragsgiver/*Client***<br>Norges vassdrags- og energidirektorat (NVE) | **Dato/*Date***<br>2016-12-09 |
| **Rettigheter til dokumentet iht kontrakt/*Proprietary rights to the document according to contract***<br>BEGRENSET: Distribueres til oppdragsgiver og er tilgjengelig for NGIs ansatte / *LIMITED: Distributed to client and available for NGI employees* | | **Rev.nr. & dato/*Rev.no. & date***<br>0 / 2016-12-09 |
| **Emneord/*Keywords***<br>Snow avalanches, hazard mapping, GIS framework, SAT-SKOGrelease areas, release probability, climate effects | | |

| **Stedfesting/*Geographical information*** | |
|---|---|
| **Land, fylke/*Country***<br>— | **Havområde/*Offshore area***<br>— |
| **Kommune/*Municipality***<br>— | **Feltnavn/*Field name***<br>— |
| **Sted/*Location***<br>— | **Sted/*Location***<br>— |
| **Kartblad/*Map***<br>— | **Felt, blokknr./*Field, Block No.***<br>— |
| **UTM-koordinater/*UTM coordinates***<br>**Sone:** 33N **Øst:** — **Nord:** — | **Koordinater/*Coordinates***<br>**Projeksjon, datum:** — **Øst:** ° ′ ″ **Nord:** ° ′ ″ |

**Dokumentkontroll/*Document control***
**Kvalitetssikring i henhold til/*Quality assurance according to* NS-EN ISO9001**

| **Rev.** | **Revisjonsgrunnlag/*Reason for revision*** | **Egenkontroll av/*Self review by:*** | **Sidemanns-kontroll av/*Colleague review by:*** | **Uavhengig kontroll av/*Independent review by:*** | **Tverrfaglig kontroll av/*Interdisciplinary review by:*** |
|---|---|---|---|---|---|
| 0 | Originaldokument | Peter Gauer | Ulrik Domaas | | |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |

| **Dokument godkjent for utsendelse / *Document approved for release*** | **Dato/*Date***<br>2016-12-09 | **Prosjektleder/*Project Manager***<br>Ulrik Domaas |
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