Effect of high elevation birch forest on snow stability

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ABSTRACT: Forest and especially evergreen conifers like pine and spruce are known to reduce avalanche formation due to their physical anchoring effect and their influence on snow pack layering through changed temperature, radiation, wind speed etc. Research shows that percentage covered by the crown reflects the forests ability to reduce avalanche danger, and crown cover is therefore often used as a measure of the forest's efficiency as protection forest. Crown cover is highest in evergreen conifer forests, but in Scandinavia, the deciduous tree species birch (Betula pubsens, subspecies alpine betula) is the most common tree species in higher elevations near the tree line. This is a small and often thin stemmed, flexible tree. Their crown is thin and field observations show that in avalanche terrain the stems of such trees have a form heavily affected by snow creep and glide and the trees are in many cases bent under the snow cover. Thus, this type of forest does not fulfill the common criteria set for protection forests and its effect on the snow cover is largely unknown. In this study we question whether typical birch forests can reduce the probability of avalanche formation through snowpack effects and anchoring. We look at cases of small avalanches in birch forest, stem densities and snow profiles inside and outside birch forest and compare observations to results from models for calculating anchoring effects.

KEYWORDS: birch, deciduous forest, protection forest, avalanche, anchoring effect

1 INTRODUCTION

The perception that forest reduces slab avalanche danger has old traditions. This is also the background for defence structures in avalanche starting zones, which in some ways imitate a forest. Forest is believed to reduce the probability of slab avalanche formation by reducing snow accumulation and weak layer formations and extension (i.e. Gubler and Rychetnik, 1991 and Bauerhansl et al., 2010), and also by anchoring the slab – i.e. taking up slope parallel forces, again reducing the stress acting on the weak layer (i.e. Haefeli, 1951; Salm, 1978 and Margreth, 2007).

Studies on both the anchoring and the snow properties effect have mostly focused on forests consisting of relatively large conifers. The effect on snow layering is largest in conifer forests with a high degree of crown cover, and crown cover has thus been used as a measure of the forests efficiency as protection forest (Bauerhansl et al. 2010 and Breien and Høydal, 2013). Guidelines for protection forest exist for countries in the Alps and in North America (Weir, 2002; Bauerhansl et al. 2010). Bauerhansl et al. (2010) set a crown cover of minimum 50 % for conifer forest. For deciduous forest the number was set to 80 % to compensate for the reduced effect of the crown in deciduous forest. Also in Norway 50 % crown cover has been proposed for conifer protection forest (Breien and Høydal, 2013).

Breien and Høydal (2013) shed light upon the fact that the high elevation forest in Norway is dominated by birch, *Betula pubsens*, subspecies alpine betula, and that the efficiency of this tree species as protection forest is largely unknown. Their crown is thin and naked throughout the winter season. Field observations show that in steep terrain the stems of such trees have a form heavily affected by snow creep and glide and the trees are in many cases bent under the snow cover. Thus, we question whether crown cover or other common density criteria set for protection forest can be transferred to this type of forest. The crown is certainly thinner, and the effect on snow layering should probably be markedly lower than for conifers of the same density. To what degree such high elevation birch forest reduces avalanche probability is important both in hazard zoning work and for skiers and other recreationists. In this study we examine cases of avalanche release in birch forest, snow profiles inside and outside forest, forest densities and compare the cases to results from calculations.

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2 FOREST'S EFFECT ON SNOW LAYERING

Most slab avalanches form when the stratigraphy is like a sandwich: a thin, weak layer between two relatively thick, cohesive layers. A general understanding is that slabs tend to fail more often on weak layers in the old snow pack (i.e. facets) in continental than in maritime climates.

Forest, especially due to the tree's crowns, affect the snow pack layering as a result of modified precipitation, temperatures and wind and can thus reduce the factors leading to instability of the snow pack.

Forested areas generally have less snow on the ground (according to Weir (2002) snow cover is reduced by 30 %), fewer faceted grains, less layering and experience less creep in the snow pack (Frey and Salm, 1990). Also, protection from wind results in less snow drift and lower probability of hard slabs. Due to lower net energy loss in forest than in open areas and higher temperatures, the existence of surface hoar and development of faceted grains is thought to be less within the forest (i.e. Gubler and Rychetnik, 1991 and Bauerhansl et al., 2010). This is especially true for evergreen conifer forests. Field measurements show that there is less snow pack layering in spruce stands than in open areas, but this is not as significant in larch stands (Gubler and Rychetnik, 1991). Gubler and Rychetnik (1991) also found that fractures are likely to propagate in larch, but not in spruce stands. We do not find any data on this for birch forests or other deciduous broadleaved trees in mountain regions.

Pomeroy and Goodison (1997) present observation data of winter leaf area index (LAI) and snow water equivalent (SWE) for aspen, pine and spruce forest. The study shows a linear trend in the relationship between LAI and SWE. SWE in spruce stands is about half the SWE in aspen stands, meaning that the ground in aspen forests accumulate twice as much snow as in spruce forests. Pomeroy and Gray (1997) show that SWE for aspen is very similar to SWE in open areas, meaning that the deciduous tree aspen to little degree protects from snow accumulation. Close to the tree line, however, experience indicate that large amounts of snow may accumulate close to the tree line due to snow drifting from the open mountains. This situation is not treated here.

3 FOREST'S ANCHORING EFFECT

Snow on the ground is always in motion, due to creep and glide. In creep, the snow grains move perpendicularly to the slope, resulting in settlement and increasing hardness and stability, and in the slope parallel direction resulting in shear deformation and instability. It is the shear deformation and shear stresses that in the end can cause slab avalanches. Creep is temperature dependent and increases with increasing temperature. Glide is defined as slip of the snowpack over an interface, usually over the ground. It occurs when the snow-ground interface is at the melting point (Salm,1978). In Norway there is little glide in dry winter snow (Larsen, 1998), but becomes important during spring.

Stems and other structures penetrating the snowpack anchors the snow by withstanding forces caused by creeping and gliding snow. A part of the snow weight is conducted to the stems and especially the ground parallel shear stresses are reduced (Salm, 1978), thus reducing the the probability of slab release. A back-pressure zone with compressive stresses forms behind the obstacle, decreasing natural creep and glide velocities in the snowpack. If the obstacle withstands the stresses, shear stresses in the back-pressure zone are reduced. If a crack forms, propagation in weak layers may be affected by the stress redistribution around the stems and eventually be stopped (Gubler and Rychetnik, 1991). If an avalanche happen to be released inside the forest, the obstacles may help to slow down the motion. The denser the forest, the larger the effect as anchors.

In the snow science community the efficiency of human built supporting structures in starting zones are often better known than the effects of forest. They are designed to simulate a natural forest, but lack the effect of the tree crown. The Swiss guidelines for defense structures (Margreth, 2007b) show how such supporting structures should be placed and how they should be dimensioned. Later in this paper we employ this approximation (Margreth, 2007a and b) to trees.

3.1 Strength of birch

Constraints for the anchoring effect are among others that the stems must be able to withstand the pressure (bending strength) and the compression strength of the snow must be higher than effective stresses (Salm, 1978).

The strength of a tree is dependent on the wood's density and the forces the tree has withstood during growth (reaction wood). Mountain forest grow slower and get denser than low land forest. Birch is the most tolerable tree species in Scandinavia when it comes to snow load and temperatures. Stuttgart table of wood strength (Wessolly and Erb, 1998) shows that birch in general is more elastic and also has higher strength than for example spruce and pine. Comparing modulus of rupture (MOR) for birch and spruce (Lavers, 1969 and Peltola et al., 2000), we see that for trees with the same diameter, birch can withstand larger forces than spruce. In juvenile age, birch is flexible and is easily bent by snow creep and glide (fig. 1). Older stems get stiffer, independent of stem diameter. When exposed to avalanches some birch trees show few or little damages, but according to Lied and Kristensen (2003) most birch forests will die if the avalanche frequency is higher than about 4 years.

Figure 1. Typical, relatively young birch forest in Hornindal with stems affected by snow movement.

3.2 Snow forces on stems

Salm (1978) was one of the first to calculate the forces from the snow pack on individual stems, as a function of stem diameter, snow depth, slope angle, creep, gliding and snow properties. In the calculation, Salm (1978) simplifies and assumes that snow is a compressible Newtonian fluid. The model calculates the length of the backpressure zone, width of lateral shear zone and tensile zone (front) where the result is the forces on the stem. It is assumed that the tree is rigid and can withstand the snow forces.

Salm (1978) finds the resultant force (R) on the stem with diameter (φ):

$$R = DF = \frac{2\pi(1+\nu)}{1+2(1+\nu)} \frac{\rho g D^3 (1+2n) \sin\psi}{\ln\left|\frac{2x_b}{\varphi}\right|} \qquad (1)$$

where

D = thickness of snowpack
F = force/unit length of stem
φ = tree diameter
υ = viscous analogue Poisson's ratio (0-0.5)
g = gravity
ρ = snow density
n = rel. glide velocity
ψ = slope angle
x_b= length of backpressure zone:

$$x_b = \frac{1}{\pi(1+\nu)\cos\psi} \frac{F}{D\rho g} \qquad (2)$$

Another approximation to a similar problem is done by Margreth (2007a) who calculates forces on obstacles (masts) as a ratio of the resultant snow forces on a rigid wall by introducing end effects. Margreth (equation 3) is designed for maximum design forces against masts, not for trees in a forest. The use of this formula for thin stems is probably outside the intention of this equation, however, the formula is consistent and its principle should be valid. The equation is based on integrated stresses, multiplied with creep and glide factors (K and N). The ratio depends on gliding and the relation between obstacle diameter and snow depth.

In Margreth (2007), snow forces per unit length on a narrow obstacle is calculated as:

$$S'_{N,M} = \rho g \frac{H^2}{2} K N \eta_F \frac{W}{D} \qquad (3)$$

The last part, η_F W/D – adjusts the formula for end effects.

$$\eta_F = 1 + c\frac{D}{W} \qquad (4)$$

where:
ρ = snow density
g = gravity
H = snow depth (vertical)
D = snow thickness (normal to slope)
W = width of structure
K = creep factor (dep. on slope and density)
η_F= efficiency factor
c = gliding intensity
N = gliding factor

3.3 Number of stems needed to stabilize the snowpack

If a fracture occurs, the idea is that if the forest is dense enough, the stems can take up a sufficient part of the slope parallel component, meaning that the slab will not move. *The question is how many trees of a certain size are needed to reduce avalanche probability significantly?*

When having calculated forces on stems (R), Salm (1978) calculated the number of stems needed to stabilize the snowpack:

minimum number of trees/ha =

$$\frac{K}{R} \frac{10^4}{\cos\psi} \qquad (5)$$

Where K is the weight component parallel to slope

$$K = \rho g D(\sin\Psi - f\cos\Psi) \qquad (6)$$

f = coefficient of friction in fracture

The equation should be valid even when only a portion of the snow pack fractures, because K/R remains the same (Salm, 1978).

4 RESULTS

During winter and summer 2013 we have studied steep (30-40^o) Norwegian and Swedish birch forests around 600-900 m.a.s.l. in several different places:

- Åre, Sweden – density characteristics (summer) in known skier triggered release areas
- Hornindal, Norway – density characteristics (summer) in randomly picked birch forest
- Hornindal and Stranda, Norway – snow profiles in old birch forest and in adjacent open areas (winter)
- Vikerfjell, Norway – snow profiles in juvenile forest and in adjacent open areas (winter)

4.1 Case study: avalanches in birch forest

We have especially studied two cases of skier-triggered avalanches released in birch forest in Åre, Sweden (figs. 2 and 3). Information (snowpack, gps-position and photos) on these avalanches were provided by Åre Avalanche Center and the release areas visited the following summer.

Figure 2. Avalanche in Åre, Sweden, around New Year 2012. Photo: Mårten Johansson, Åre Avalanche Center

Figure 3. Skier triggered avalanche in Åre, Sweden. Photo: Anna Henjer

During winter 2013, several skier-triggered avalanches occurred near the ski resort Åre, Sweden, both in open mountain terrain and in forest. They were released due to a weak layer of facets (pers. comm. Mårten Johansson, Åre Avalanche Center). The weak layer was a result of weeks of cold weather after rain. A rain crust worked as a vapour barricade, and a high temperature gradient built a layer of facets below the crust. The avalanches in the birch forest were small avalanches, size 1, according to the Canadian size classification.

Fieldwork during summer 2013 shows that the forest in the release areas was old and tall with tree heights of around 3-5 m (figs. 4 and 5). Few juvenile trees and shrubs were found. The forest showed little signs of damage from creep and avalanches.

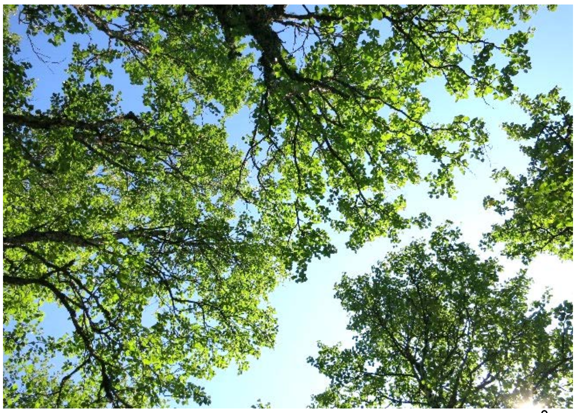

Figure 4. Summer photo from release area in Åre showing crown cover in summer.


Figure 5. Summer photo from one of the release areas in Åre.

4.2 Snow profiles

Snow profiles were dug during winter 2013 in maritime climate in Stranda and Hornindal (Norway) and in continental climate in Vikerfjell (Norway). The snow profiles show that the same kind of layering existed in the mature birch forest as in adjacent, open terrain. The most marked difference was weaker crusts, and lack of surface hoar inside the forest.

In areas with shrub-like birch and branches bent under the snow cover, the difference in snow pack is larger. Shrubs, thin trees and branches bent under the snow cover results in pockets of air within the snow. Here, facets get room to grow. Also, the organic material conducts heat. Snow pack studies from Vikerfjell show that snow can freeze to buried branches resulting in a reinforcement.

4.3 Stem density measurements

Density measurements (600-900 m.a.s.l.) of typical birch forest close to the forest line were made during summer 2013 in Hornindal (maritime climate, Norway) and in Åre (continental climate, Sweden). The density measurements in Åre were done in the areas where avalanches were triggered by skiers winter 2012-2013. We counted trees in 4 m radius circles, and put the trees in 9 different classes according to height and tree diameter at breast height (DBH). An example from Åre is shown in Table 1.

Table 1. Example of density measurements, Åre

Diameter:	0-5 cm	5-15 cm	>15 cm	Tot.>2m/5cm	Stems/haa
Height:					
0-2 m					
2-5 m		32	4		
>5 m		2			
				38	7600

We found that common densities of stems of minimum DBH 5 cm and larger was around 7-800 stems/haa, with a mean DBH of 12 cm. The lowest registered density was about 5800 stems/haa. In Åre, many trees had a DBH just below 15 cm and most trees had a height close to 5 m, relatively independent of diameter. About 1000 stems/haa had a DBH of more than 15 cm. We found that the trees were mainly older, thicker and taller in Åre than in Hornindal. It is noteworthy that forest line in this western part of Norway (Hornindal) has risen due to reduced grassing and less fire wood logging during the last half century (Breien and Høydal, 2012).

4.4 Use of models to calculate anchoring effects

We have compared the force models of Salm (1978) and Margreth (2007a), and see that for small stem diameters and low slope angles Salm's model gives twice the forces on each stem compared to Margreth's model, especially with little or no gliding. With high values of gliding (N=2), we get more similar results.

In this paper we focus on dry avalanches in Scandinavia and assume no gliding. In lower latitudes like in the Alps, exposure is of higher importance and results in larger degree of gliding in south-facing slopes. In the calculations we have chosen to apply 1.0 m snow depth (D). In the following we have used equation (3) for calculating forces on stems and equation (5) to find minimum number of stems to stabilize the slope and then compared the results to the birch densities we found in Norway and Sweden.

We see that the forces are higher the thicker the snow height, the steeper the slope and the thicker the stems. The required number of trees decrease with increasing tree dimensions and snow depth, but increases with slope angle. Slope is the single most important component in the calculation. When using DBH of 0.05-0.2 m, we find that combination of Margreth's force equation (3) and Salm's tree density equation (5) gives densities needed for avalanche protection of approximately 2000-3000 trees/ha in 30^{o} terrain, 5000-6000 trees/ha for 35^{o} slopes and 6500-8000 trees/ha for 40^{o} slopes, depending on tree diameter (fig. 6).

Our fieldwork in different climates in Scandinavia show that steep (27-35^{o}) birch forests in altitudes 600-900 m.a.s.l. with tree heights of 3-5 m have densities between 5800/ha and 12000/ha, densities that are quite high when comparing to the values resulting from equations (3) and (5), and should thus be enough to stabilize the slope.

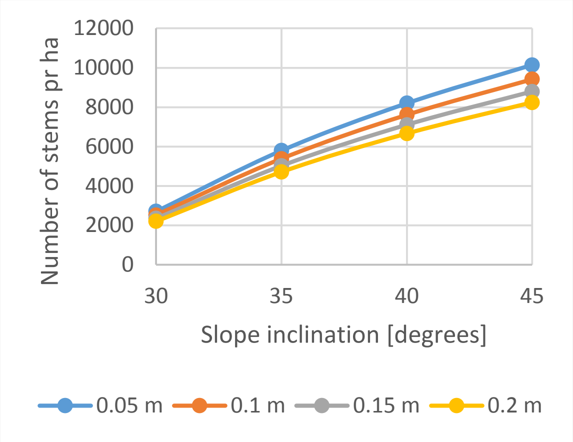

Figure 6. Density of stems needed to stabilize the snowpack according to equation (3) and (5), with different stem diameters and slope angles

5 DISCUSSION

5.1 Snow cover

Our field work indicate that mature, tall birch forest only to a slight degree affects the snowpack, whilst birch of shrub size and thin, juvenile birch bending below the snow surface alters the snow layering compared to in open areas. Case studies from Åre, Sweden, show that at least small avalanches do occur in dense, tall birch forest and that crystal growth and faceting happen more or less to the same extent as in the open areas. The fact that the weak layer responsible for the avalanches in Åre was present both in open areas and within the forest shows that weak layer building due to temperature gradient occur also in relatively dense birch forests. This is in agreement with findings from Gubler and Rychetnik (1991), who state that deciduous forest like larch do not alter the snowpack to the same degree as evergreen conifers. Our studies indicate that the naked crown of birch forest to little degree changes the microclimate. In fact, dripping from tree crowns might cause crusts that work as vapour barriers, enhancing facet growth during cold periods. We thus propose that persistent weak layers like facets might be as common in birch forests as in open terrain and that birch forest avalanches might be more probable in continental climates than in maritime climates.

However, surface hoar relatively abundant in open areas just outside the forest at our tests sites in Hornindal was absent inside the birch forest. Birch forest will to some degree protect from winds, and surface hoar near openings and close to the forest edge, might sustain for a longer period than in the open mountains. Surface hoar also forms most effectively in shadow, but with an uncovered view to the sky, as can be the case near limits of the birch forest. Surface hoar close to the tree line and in birch forest openings might thus be of extra importance as potential weak layers if covered by new snow.

According to Pomeroy and Goodison (1997) and Pomeroy and Gray (1997) aspen forested areas accumulate nearly as much snow as open areas. We assume that the values of SWE for birch are similar to those for aspen. Forest protects from wind resulting in reduced snow drift. Most likely, this results in thinner and softer windslabs in forested terrain. We believe that spruce is more effective in protecting from wind, due to the density and height of the crown, but the wind effect is still there in birch. Due to this, spontaneous avalanches following snowstorms are probably less likely in birch forests than in open terrain. This agrees with the recent findings of Teich et al. (2012). However, less wind exposure and snow drift also results in softer and less cohesive snow. Uncohesive, new snow will easily flow between stems, and soft slabs will transfer less force to stems than hard slabs.

Shrubs and smaller trees bent under the snow cover might stabilize the snowpack to a larger degree than tall birch do. Shrubs and branches bent under the snow cover enhances crystal growth, but heat transfer may also freeze the branches to the snow cover. The layers of weak facets will grow thick and the roughness of the layers is high. When it comes to slab avalanches, thin, weak layers are more efficient in propagating the fracture than thick layers. Shrubs might stabilize a shallow snowpack, but as the snowpack grows, the more superficial layers will not be affected to the same degree. Also, the thicker areas of facets near ground will form a loose base and might increase the danger for example of wet avalanches during spring.

5.2 Densities and anchoring effects

Calculations using equations (3) and (5) suggest that forest densities of 2000-3000/ha should stabilize the snowpack in 30º slope terrain just by the anchoring effect of the stems. The Swiss guidelines (Bauerhansl et al., 2010) use crown cover as a measure for protection efficiency, taking both anchoring and snow layering effects into account. In Breien and Høydal (2013) we used DBH to calculate crown cover of birch (Widlowski et al., 2003), and found that to achieve a minimum crown cover of 80 % (Bauerhansl et al, 2010), a density of around 2500 stems/ha of mean diameter 10 cm should be enough. Case studies from Åre, Sweden, however, show that small avalanches can be triggered in dense, tall birch forest with densities of 7-8000 stems/ha, at least when an artificial trigger like a skier is present.

We think that crown cover is a valid measure for protection forest when it comes to conifers, but it is not straight forward to transfer this to deciduous birch forest due to its thinner crown. Pomeroy and Goodison (1997) present data that indicate that LAI (leaf area index) is a parameter that might be fruitful to further study for comparison of canopy effects in deciduous and coniferous forests.

We propose that the anchoring effect on its own in many cases is not enough to stabilize the snow pack completely, and that it is difficult to set specific density criteria as in Salm (1978) and Bauerhansl et al. (2010) for Scandinavian birch forest. Our findings support the opinion that the forest's effect on the snowcover is the main factor reducing avalanche probability in forested terrain. The thin canopy of birch results in little effects on the snow cover, again resulting in limited avalanche protection effect from birch forest.

We stress that snowpack characteristics such as slab hardness and propagation ability are important parameters that makes it difficult to give strict guidelines for protection forests. A hard slab will transfer more stress to the trees even if they are sparse, whilst a soft slab will be less affected by the trees. Also, we argue that hard slabs might be rare in forest due to less wind exposure. Uncohesive snow cannot be hindered by forest and can easily flow between tree stems (Imbeck and Meyer-Grass, 1988), for example wet snow and new, dry snow. The forest will have no anchoring effects on such avalanches as the cohesion of the snow is largely reduced.

We emphasize that the cases of avalanches in birch forest in this paper are small, skier triggered avalanches with short runouts, whilst the densities in the guidelines for protection forest are meant for large, destructive avalanches reaching terminal velocities. However, propagation was a fact in our examples, and release as well. For skiers, even small avalanches can be a serious threat in forested terrain. We stress that more studies on propagation ability and velocity reduction in forested terrain are needed to understand whether such avalanches can grow large and destructive.

6 CONCLUDING REMARKS

We believe that avalanches in birch forests are less common than in open areas, however, coniferous forest is much more effective in protecting from avalanches than deciduous forest is. Avalanche cases from this winter show that facets can grow and produce weak layers, and that small, dry slab avalanches can be released by skiers in dense birch forests. Due to its thin canopy, birch affects the growth of facets only to a slight degree, and a dense birch forest seems not to be enough to hinder avalanche release under such circumstances. This indicates that the forest's effect on snow layering is essential in preventing avalanche formation and more important than anchoring alone. In guidelines for protection forest, crown cover, which takes into account both anchoring and snow layering effects, has been used as a measure of the protection effect. This method works well for conifer forests, but might not be the optimal solution for deciduous forest.

We propose that in climates where crystal growth/faceting constitutes a large percentage of avalanche causes, mature birch forest is not effective in reducing the probability of avalanche triggering - due to its limited effect on snow pack layering. In climates where heavy snowfalls and wind are predominant, avalanche release in birch forest might be less common. To what degree the stems limit fracture propagation and the size of avalanches in birch forest needs further studies.

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