Catena 165 (2018) 567–575

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Spatial evaluation of snow gliding in the Alps

Georg Leitinger[a,*], Katrin Meusburger[b], Johannes Rüdisser[a], Erich Tasser[c], Janette Walde[d], Peter Höller[e]

[a] Department of Ecology, University of Innsbruck, Sternwartestraße 15, A-6020 Innsbruck, Austria
[b] Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), Zürcherstrasse 111, 8903 Birmensdorf, Switzerland
[c] Institute for Alpine Environment, EURAC.research, Viale Druso 1, I-39100 Bolzano/Bozen, Italy
[d] Department of Statistics, University of Innsbruck, Universitaetsstrasse 15, 6020 Innsbruck, Austria
[e] Department Natural Hazards, Federal Research Centre for Forests (BFW), Rennweg 1, A-6020 Innsbruck, Austria

ARTICLE INFO

Keywords:
Winter erosion
Wet avalanches
Landslides
High-elevation afforestation
Soil erosion
GIS

ABSTRACT

The slow downhill motion of snow on the ground, referred to as snow gliding, impairs afforestation, increases the predisposition for landslides, fosters winter soil erosion, and coincides with the occurrence of glide-snow avalanches. This study identifies areas with a high chance for severe snow gliding for an area covering > 20,000 km^2 in the Central and Eastern Alps. The *Spatial Snow-Glide Model* (SSGM) was used to map potential snow gliding areas (i.e. snow gliding distances). The results revealed 56% of the investigated area to be potential snow gliding areas. Nearly 2000 km^2 (17%) were prone to snow gliding distances of > 112 cm per winter period, indicating a high vulnerability for both glide cracks and glide-snow avalanches. Taking the inter-annual variability of winter precipitation into account, which turned out to be highest in the usually drier southern part, another 5690 km^2 were found to have a high risk for snow gliding damages. For planning purposes of on-site mitigation measures the *Guidelines to Identify Snow-Glide Areas* (GISGA) were validated to corroborate the sequential application of SSGM and GISGA for comprehensive assessment of snow gliding at landscape scale. We conclude that the application of SSGM and GISGA provides an appropriate evaluation framework for regional stakeholders to implement adequate steps to prevent critical snow gliding.

1. Introduction

The Alps are characterized by an actual tree line that is lower than the potential tree line because of centuries-long land management in alpine areas (Pecher et al., 2011). In recent decades, socioeconomic changes have led alpine areas to be abandoned for grazing and fodder production (Tappeiner et al., 2008; Zimmermann et al., 2010; Flury et al., 2013). Land abandonment leads to secondary succession (Alewell and Bebi, 2011) thereby affecting snow gliding. According to McClung (1981) and McClung and Schaerer (2006) snow gliding is defined as the transitional slip of the entire snowpack over the ground. Gliding of snow is seen as the main driver of winter soil erosion (Freppaz et al., 2010; Ceaglio et al., 2012; Korup and Rixen, 2014; Meusburger et al., 2014; Stanchi et al., 2014), increases the predisposition for landslides in spring (Tasser et al., 2003), and negatively affects afforestation (uprooting of plants) (Höller et al., 2009; Feistl et al., 2014). Additionally, snow gliding has proved to be a reliable indicator of glide-snow avalanches (Clarke and McClung, 1999; Höller, 2014a) and it is assumed that the relative proportion of glide-snow avalanches – also referred to as "full-depth avalanches" (Feick et al., 2012; Mitterer and Schweizer, 2012) – increases (Martin et al., 2001). Numerous accidents caused by gliding snowpacks and glide-snow avalanches have been observed in recent years (Ancey and Bain, 2015) and future land-use/land-cover (LULC) trends continue affecting frequency and intensity of snow gliding by altering vegetation types (i.e. vegetation roughness). In the period between 1980 and 2010, between 30% and 70% of the usable agricultural areas have been abandoned in the European Alps (Tappeiner et al., 2008), leading to increased snow gliding during secondary succession unless shrubs and young trees are established (Newesely et al., 2000).

To successfully inhibit snow gliding, preventive actions must be taken. Even though spatially explicit information on areas prone to snow gliding in topographically complex terrain is a prerequisite for evaluating possible impacts and planning or adapting actions for glide reduction, this information is hardly available. Leitinger et al. (2008) published the *Spatial Snow-Glide Model* (SSGM) which allows mapping of snow gliding distances as a lumped sum for the winter period based on the parameters *forest stand*, *slope angle*, *slope aspect*, *vegetation*

* Corresponding author.
E-mail address: georg.leitinger@uibk.ac.at (G. Leitinger).

https://doi.org/10.1016/j.catena.2018.03.001
Received 20 October 2016; Received in revised form 20 November 2017; Accepted 1 March 2018
Available online 14 March 2018

roughness, and *winter precipitation*. Although this model is under steady development (i.e. extending the parameterization database) and its reliability was further demonstrated by Meusburger et al. (2014), it has some significant drawbacks at the slope scale as it cannot include surface roughness.

In this context, another promising concept for assessing snow gliding areas was published by Höller (2012) and proposed as *Guidelines to Identify Snow-Glide Areas* (GISGA). GISGA allows accurate evaluation of the snow gliding potential at local scales by considering *geographical region*, *slope angle*, *slope aspect* and *surface roughness*. GISGA was especially designed as a field method for practitioners, but application at the landscape scale is currently not possible as large-area assessment of the surface roughness using remote sensing techniques is too imprecise and field surveys are very labor-intensive. Additionally, GISGA has not yet been validated with snow gliding measurements.

The aim of this study is to promote the sequential application of these two approaches reinforced by the validation of GISGA using snow gliding measurements in three study areas in the Alps. We propose a new practical and cost-effective management scheme that comprehensively evaluates snow gliding in two steps: First, a spatially explicit map of snow gliding distances is estimated with the SSGM to identify critical areas (landscape scale). Second, on-site applications of GISGA on critical areas identified by the SSGM (slope scale) are conducted. The results allow the planning of suitable steps for mitigation, which are also briefly discussed.

Our specific objectives are:

- to validate GISGA by snow gliding measurements in three different study areas,
- to model snow gliding distances with the SSGM for the Central and Eastern Alps with special emphasis to identify areas with high chance for severe snow gliding (which can be refined using GISGA), and
- to describe peculiarities when using the SSGM at larger scales including regions showing strongly varying inter-annual winter precipitation.

2. Materials and methods

2.1. Study area

GISGA was validated at three different sites: (1) at the long-term socio-ecological research (LTSER) site 'Kaserstattalm' (Stubai Valley, Tyrol, Austria, WGS84 11.31E, 47.13N), (2) at the 'Waltner Mähder' (Passeier Valley, South Tyrol, Italy, WGS84 11.28E, 46.84N), and (3) at 'Urseren Valley' (Canton Uri, Switzerland, WGS84 8.52E, 46.61N) (Fig. 1).

For the 'Kaserstattalm' site, average annual air temperature and mean annual precipitation at 1900 m a.s.l. are 3.0 °C and 1097 mm for the period 1981–2010. Approximately one-third of precipitation is falling as snow. By the middle of the 20th century, the predominant LULC of the study area was 'managed grassland' (mowing 1–2 times per year and grazed in autumn). As part of reduced management and lower grazing intensities since the 1950s, more than half of these grasslands have been abandoned, resulting in a successive change to shrub lands and young forest stands. Field measurements between 1997 and 2007 provide a comprehensive data pool of snow gliding distances linked to a broad range of influencing parameters (see Newesely et al., 2000; Leitinger et al., 2008; Höller et al., 2009 for details).

For the 'Waltner Mähder' site, the average annual air temperature is around 3.6 °C and the mean annual precipitation is 1041 mm at 1618 m a.s.l. (1971–2000), with 30% falling as snow. Snow gliding measurements on meadows and pastures (different degree and intensity of management) as well as forested areas have been conducted between 1997 and 2004.

For the 'Urseren Valley' site, the average annual air temperature for the years 1980–2012 is around 4.1 °C at 1442 m a.s.l., and the mean annual precipitation is 1457 mm, with 30% falling as snow. Snow gliding measurements at the four different LULC-types hayfields, pastures, pastures with dwarf shrubs, and abandoned grassland covered with *Alnus viridis* were conducted between 2009 and 2010 (Meusburger et al., 2014).

The *Spatial Snow-Glide Model* (*SSGM*) was applied for the entire area of Tyrol ('A', Austria) and South Tyrol ('B', Italy) in the Central and Eastern Alps (Fig. 1). This region covers 20,036 km^2 at elevations ranging from 205 m to 3905 m a.s.l. Five climate regions can be distinguished (based on: Fliri, 1975; Wakonigg, 1975), which are mainly characterized by different amounts of winter precipitation (Fig. 1).

Winter precipitation was computed by taking the mean of the precipitation sum between December and March over the years from 1981 until 2010. The comparison of the five zones with respect to the winter precipitation showed a strong decline in precipitation (in brackets we provide mean ± standard deviation): (1) the northern part of the Alps where the southerly moving mass of air runs up against the mountain range (orographic uplift) causing large amounts of precipitation (391 ± 82 mm), (2) the intermountain region in the North obtains less precipitation (298 ± 31 mm), followed by (3) the inner Alpine region with a more continental climate (238 ± 56 mm), (4) the intermountain region in the South (203 ± 17 mm), and (5) the driest region in the South (154 ± 55 mm). The study area was strongly affected by historical LULC change driven by alpine farming and agricultural production for decades. Zimmermann et al. (2010) identified two main trends of LULC: (1) 'grassland abandonment' since the mid-19th century, and (2) 'continuous grassland farming'. 'Grassland abandonment' is the most frequent trend, often occurring in the subalpine regions, but also in the montane and colline regions (mainly in the southern Italian Alps). The need for lower production costs resulted in the reduction of time-consuming traditional practices and abandonment of unproductive sites in the slope regions and subalpine zone (Tappeiner et al., 2008). Simultaneously, continuous grassland farming which is the specialization in cattle farming associated with intensified fodder production on the agriculturally favored valley floors is seen as an adaptation strategy (Gellrich et al., 2007; Flury et al., 2013).

2.2. Guidelines to identify snow-glide areas (GISGA)

Höller (2012) has introduced a practical method to identify areas that are prone to snow gliding and to point out appropriate measures to prevent critical snow gliding rates (with regard to the damage of juvenescent trees).

He defined the geographical region, the roughness of the ground, the slope inclination and the slope aspect as the four most important influencing parameters. For each influence parameter three increments have been provided (yielding in total 81 combinations).

Slope angle (gradations: 25–30°; 30–35°; > 35°) and slope aspect (gradations: SE-SW; E-SE and SW-W; NW- NE) follow classifications published by Newesely et al. (2000), Höller (2001, 2014a, 2014b), and Leitinger et al. (2008). Geographical region (gradations: pre-alpine region; intermountain region; inner-alpine region) serves as proxy for snow heights and follows the classification scheme of Wakonigg (1975); GISGA was primarily intended to protect high-elevation afforestation. The underlying field measurements cover the range between 1800 m and 2200 m a.s.l. for the above-mentioned geographical regions. Surface roughness was indicated by the height of mounds (gradations: 0.1 m; 0.2 m; 0.3 m), whereas it was supposed that the ground surface can be approximated by a sine wave (McClung, 1975), with A (amplitude) the height of mounds and λ_o (wave length) the distance between two mounds.

Although only three increments per parameter are provided, these are – in particular for practical use – adequate to reflect the various potentials of snow gliding and to specify the corresponding relative snow gliding values.