DOI: 10.5152/forestist.2021.20060
Forestist 2022: 72(1): 62-72

ISTANBUL UNIVERSITY CERRAHPAŞA

Original Article

Generating Avalanche Hazard Indication Map and Determining Snow Avalanche Protection Forests in Çaykara-Trabzon (NE-Turkey)

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ABSTRACT

In this study, a GIS-based large-scale hazard indication map was generated for Çaykara District (Trabzon, NE Turkey) by taking the forest into account in the determination of potential release zones. In addition, the forest stands with potential protection function (FS-PPF) were determined and mapped in terms of defined degrees of protection (high, moderate, moderate-low, low, and very low). In total, 5525 release zones covering 8446 ha were determined in Çaykara District, whereas the areas exposed to avalanche hazards covered 22088 ha. In addition, 6629 ha of FS-PPF were mapped, 72% of which fell into the high FS-PPF protection class and included pure or mixed coniferous forest stands. Moreover, 22% of the entire FS-PPF mapped in the study area fell within the very low protection class. In terms of forest stand types, it was revealed that 54% of the FS-PPF against snow avalanches consisted of pure coniferous or coniferous mixed with other tree species, 24% were mixed coniferous and broad-leaved tree species (coniferous tree species being predominant), 11% were mixed broad-leaved and coniferous tree species (broad-leaved tree species being predominant), and 11% were pure broad-leaved tree species or broad-leaved species mixed with others. In this study, we have proposed a procedure to depict the different degrees of protection provided by the FS-PPF against snow avalanches in order to facilitate functional planning goals in Turkish forestry. The results showed that the FS-PPF map could be integrated within forest management plans and could be used as a base in the planning of silvicultural operations.

Keywords: Avalanche protection forest, forest stands, hazard indication map, snow avalanche

Introduction

Snow avalanches have significant impacts on recreation, transportation, property, and resource industries in snow-covered mountainous areas worldwide (Stethem et al., 2003). For this reason, the increasing importance of mapping snow avalanche hazards has been recognized, especially for providing information about the size, frequency, and areal extent of potential avalanche danger zones. Avalanche hazard maps are also essential tools used by experts in evaluating avalanche risks (Brugnot, 1999). Mapping snow avalanche hazards in the European Alps dates back as early as the 19th century (Coaz, 1881; Frutiger, 1980), and today, it is carried out in many countries that suffer snow avalanches such as Switzerland, Austria, France, Italy, Germany, Japan, Norway, Spain, Slovenia, Canada, and the USA (Oller et al., 2013; Rudolf-Miklau et al., 2015). In fact, the mapping of avalanche hazards and risks, which includes the elaboration of scientific basics and the cartographic representation, is generally categorized as hazard (indication) maps, process maps (intensity maps), hazard zone plans, and risk maps (Rudolf-Miklau et al., 2015). Hazard indication maps are tools providing a rough overview of which areas can expect avalanche danger, and they are the only source of information about the location and spatial extent of an avalanche hazard (Rudolf-Miklau et al., 2015). Some examples of GIS-based hazard indication mapping in literature are given by Aydın and Eker (2017a), and Bühler et al. (2018a, b). However, the documentation of past snow avalanches, including detailed descriptions of their properties (e.g., magnitude, area affected, type of damage) and their effects on and interactions with ecosystems are important in hazard/risk assessment. In Turkey, around 24 lives have been lost annually due to snow avalanches (based on an incomplete database) (Aydın et al., 2014); however, no detailed documentation on avalanches is available. Thus, mapping snow avalanche hazards has become an important phase of snow avalanche work in Turkey. However, in Turkey, hazard mapping work does not fall under the responsibility of any specific public institution. Frequent changes have been made in the organizational schemes of governmental institutions tasked with hazard mapping, and yet,

Cite this article as: Aydın, A., Eker, R., & Odabaşı, Y. B. (2022). Generating avalanche hazard indication map and determining snow avalanche protection forests in Çaykara-Trabzon (NE-Turkey). *Forestist*, 72(1), 62-72.

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Received:
December 16, 2020
Accepted:
February 20, 2021
Available Online Date:
August 27, 2021

achieving international standards in this work have not been realized. However, in forest areas, the Turkish Forest Service is responsible for the hazard and risk mapping of natural hazards (Aydın et al., 2014).

Snow avalanches also cause serious damage to mountain ecosystems by interacting with their dynamics via a range of scales (Bebi et al., 2009). Avalanche disturbances primarily affect subalpine forests. Especially when they occur frequently and with substantial impact, a forest is either prevented from becoming established or is regularly destroyed at an early developmental stage and is, therefore, ineffective as a protection forest (Brang et al., 2006). According to the Canadian snow avalanche size classification system (McClung & Schaerer, 2006), large avalanches with a mass exceeding 10^4 t and impact pressure higher than 500 kPa are capable of destroying 4–40 ha of forest area. In other words, forests cannot stop large avalanches from releasing above the tree line and have a limited braking effect. The trees may be destroyed through various mechanisms including fracturing and overturning, and they may be entrained into the flow (Bartelt & Stöckli, 2001; De Quervain, 1978). However, forests have a retarding effect on lower-energy small- to medium-sized avalanches releasing with a flowing depth of 1–2 m from zones located near the tree line (Feistl et al., 2012; Margreth, 2004). Along with the important impact of snow avalanches on forest structure and function, forest stands can significantly influence the formation, size, frequency, intensity (magnitude), and run-out distance of snow avalanches (Bebi et al., 2001; Frehner et al., 2005; McClung, 2003). The protective role of the forest is most pronounced in the case of forests located inside the avalanche release zone (Viglietti et al., 2010). The presence of trees can significantly reduce the formation of avalanches by preventing the formation of large, homogeneous snow areas (In der Gand, 1978; Schönenberger & Brang, 2004) and acting as obstacles to the snow avalanche mass (Brang et al., 2006).

In combination with the impact of the topography on avalanches releasing in forests, the protection function of forests is generally considered in relation to the forest structure (crown/canopy closure/coverage, tree/stem density, composition of tree species, and size and distribution of forest gaps) (Bebi et al., 2001; Nairz et al., 2015; Teich et al., 2012; Viglietti et al., 2010). For this reason, a comprehensive understanding of the interactions between forest stand structures and snow avalanche formation is essential in forest management planning and in making decisions on appropriate silvicultural operations. One of the important parameters related to stand structure is crown closure since it influences the characteristics of the snow beneath the forest (Viglietti et al., 2010). Depending on snowfall intensity and tree species composition (Motta, 1995), the snow depth in forests is lower than in open areas (Pomeroy & Brun, 2001). Up to 60% of the total annual snowfall can be intercepted by the boreal forest canopy (Hedstrom & Pomeroy, 1998; Montesi et al., 2004). In terms of tree height, which is another important parameter, forest stands should be composed of tree species two times higher than the snow depth to stabilize the snowpack (Saeki & Matsuoka, 1969). McClung (2003) reported that release zones in areas covered by vegetation were characterized by a tree height of less than 2 m. The protection function of a forest against snow avalanches is also connected to stem density and diameter at breast height (DBH) (Schneebeli & Meyer-Grass, 1993). Meyer-Grass (1987) and Schneebeli & Meyer-Grass (1993) considered a DBH of greater than 16 cm necessary for effective stabilization, whereas a DBH of greater than 8 cm was proposed by Frehner et al. (2005). Gaps are also another important parameter to be considered in terms of probability for the release of an avalanche within the forest. Bebi et al. (2001) stated that the snow avalanche release probability was high in the presence of gaps with a width of 15 m or in very open forests (crown closure $< 40\%$) located on steep slopes.

Identification of forests having a protective function against snow avalanches could be carried out by combining numerical simulations of dynamic snow avalanche models and GIS-based methods (Monti et al., 2018). Gruber and Baltensweiler (2004) assessed the protective function of the forest within the SilvaProtect project in Switzerland by combining automated snow avalanche release area identification algorithms. Teich & Bebi (2009) proposed a risk-based approach to evaluate the protective effect of mountain forests against natural hazards in a spatially explicit manner. Monti et al. (2018) identified forests with protective functions by comparing the potential release area determined with and without considering the forest. They evaluated the protection function of the forest as active or passive protection depending on the crown closure. In the latest study within a similar scope, Brožová et al. (2020) aimed to determine forest parameters such as tree height and crown closure of deciduous and evergreen tree species for avalanche simulation using remote sensing data. In addition to the identification of forest areas having a protective function against snow avalanches, interactions between mountain forests and snow avalanches have been assessed (Bebi et al., 2001, 2009; Casteller et al., 2018; Feistl et al., 2012; Schneebeli & Meyer-Grass, 1993; Teich et al., 2012, 2019). Bebi et al. (2001) evaluated 22 forest parameters including tree height (meter), percentage of trees with different DBH, crown closure, volume of dead woody debris (percentage), etc. using stereoscopic assessment and image processing techniques. In one of the latest studies, Teich et al. (2019) considered forest stand parameters when evaluating the potential impacts of forests infested by bark beetle on avalanche formation and forest snowpack.

The establishment and/or maintenance of the protection function of a forest stand against snow avalanches require especially crucial and complex forest management strategies. However, the determination and mapping of the FS-PPF against snow avalanches are prerequisites for proper technical and silvicultural maintenance or improvement of the protective function in forest management (Monti et al., 2018). Therefore, decision-makers need forest inventories that provide accurate information as their main data resources. The primary objective of forest inventory work is to estimate wood availability in specific areas (Kangas et al., 2006). Periodical inventory surveys based on ground sampling have been implemented for more than a century (Vidal et al., 2016). In Turkey, ground sampling surveys for forest inventory work have been carried out at 10- or 20-year intervals at the forest enterprise level (Kayacan et al., 2016). Today, forest stands are first delineated into polygons based on the interpretation of medium-scale (e.g., 1/10000 or 1/15000) aerial photographs (LeMay et al., 2008) and then integrating them with ground sampling surveys indicating measurements of individual trees in sample plots. These are used to create vector-based maps, called "forest cover maps" or "forest stand type maps". The common measurements used in forest inventories for forest management plans include DBH, timber volume, basal area, and number of stems (Bulut et al., 2016; Vatandaşlar & Zeybek, 2020). Many of these are included in the attributes of forest stand type maps created in a vector-based format.

The present study included two objectives: (1) the generation of a large-scale snow avalanche hazard indication map for Çaykara District (Trabzon, Turkey), and (2) the determination of FS-PPF against snow avalanches and their classification into different degrees of protection.

The study not only identified the FS-PPF against snow avalanches using a method similar to that of Monti et al. (2018) but also classified them into five protective degrees on the resulting map. Stand maps were used in the classification because they included tree species and their distribution (pure or mixed), crown closure, and developmental stage. The Çaykara District was selected as the study area because of its exposure to a multitude of natural hazards such as floods, landslides, snow avalanches, and rockfalls and because of its mountainous topography with steep slopes and high elevation. However, snow avalanches are the most hazardous events in the region. The region is also covered by dense forests and includes the Uzungöl Nature Conservation Area, one of the most important nature and tourism areas in NE Turkey.

Material and Methods

Study Area

Çaykara District (Trabzon, Eastern Black Sea Region of Turkey), covering 56581 ha, was selected as the study area (Figure 1). The district includes the Uzungöl Nature Conservation Area (Figure 1), one of the most important nature and tourism areas in NE Turkey. Uzungöl was declared a "Tourism Center" in 1990, and also, with the decision of the Council of Ministers, a "Special Environmental Protection Area" in 2004 (Atasoy, 2010). According to the Turkish Statistical Institute (TUIK), while the total population was 38221 in 1965, it fell to 12874 in 2015. Although more than 84% of the population of Çaykara District lived in the villages until 2012, the population of the district and the villages has decreased by 65% and 70%, respectively, due to significant migration from the region. The settlements are scattered due to the topography of the region. In other words, the sites suitable for construction and agricultural activities are limited. The most suitable locations for settlement and agriculture in terms of topography and in terms of generating adequate incomes for the economic livelihood of the inhabitants are found around the lake, but these also present risks of natural hazards. There is no industrial sector in the region, and in the past, the population, who were engaged in agriculture and/or the forestry sector, preferred to settle in the areas surrounding the lake.

The district is covered by dense forests, with broad-leaved forests found up to an altitude of 900 m a.s.l., mixed forests at elevations between 900 and 1300 m a.s.l., and coniferous forests at elevations higher than 1300 m a.s.l. The typical timberline in the study area is 2200 m a.s.l. The average altitude and slope of Çaykara District with its harsh topography are 1662 m (ranging from 246 to 3385 m a.s.l.) and 34°, respectively. In the region, 49% of the total area is located on slopes between 0° and 28°, 48% on slopes between 28° and 55°, and the remaining on slopes greater than 55°. The mean annual precipitation of the region is 1111 mm, and the mean annual temperature is 13.3°C.

The region is exposed to multiple natural hazards such as floods, landslides, snow avalanches, and rockfalls. Even though snow avalanches are the most hazardous events and frequent phenomena in the region, no detailed and systematic documentation of the events has been carried out. The latest event was a deadly snow avalanche on January 10, 2015, in the Uzuntarla region (Figure 1) that fatally buried five workers employed at the construction site of a hydroelectric power plant. Aydın et al. (2015) prepared a detailed analysis and back-calculation modeling of the event. Another important settlement exposed to snow avalanches is Yaylaönü village (Figure 1), where the earliest recorded avalanche event occurred in the 1850s, causing three fatalities and the destruction of three buildings. Destructive avalanches also occurred in Yaylaönü village in 1974, 1981, and 1993. In addition, there have been snow avalanches in many places in the study area without loss of life, but sometimes with injuries. Snow avalanches are known to have occurred in Demirkapı-Dursuoğlu village (Figure 1) in the 1890s, in 1955, 1993, and 2011. One snow avalanche event that occurred in the 1890s destroyed four houses and caused several injuries, but there was no loss of life. In 1955, an avalanche released from the same starting zones injured one person. Small- to medium-sized avalanches have been observed almost every year in the region.

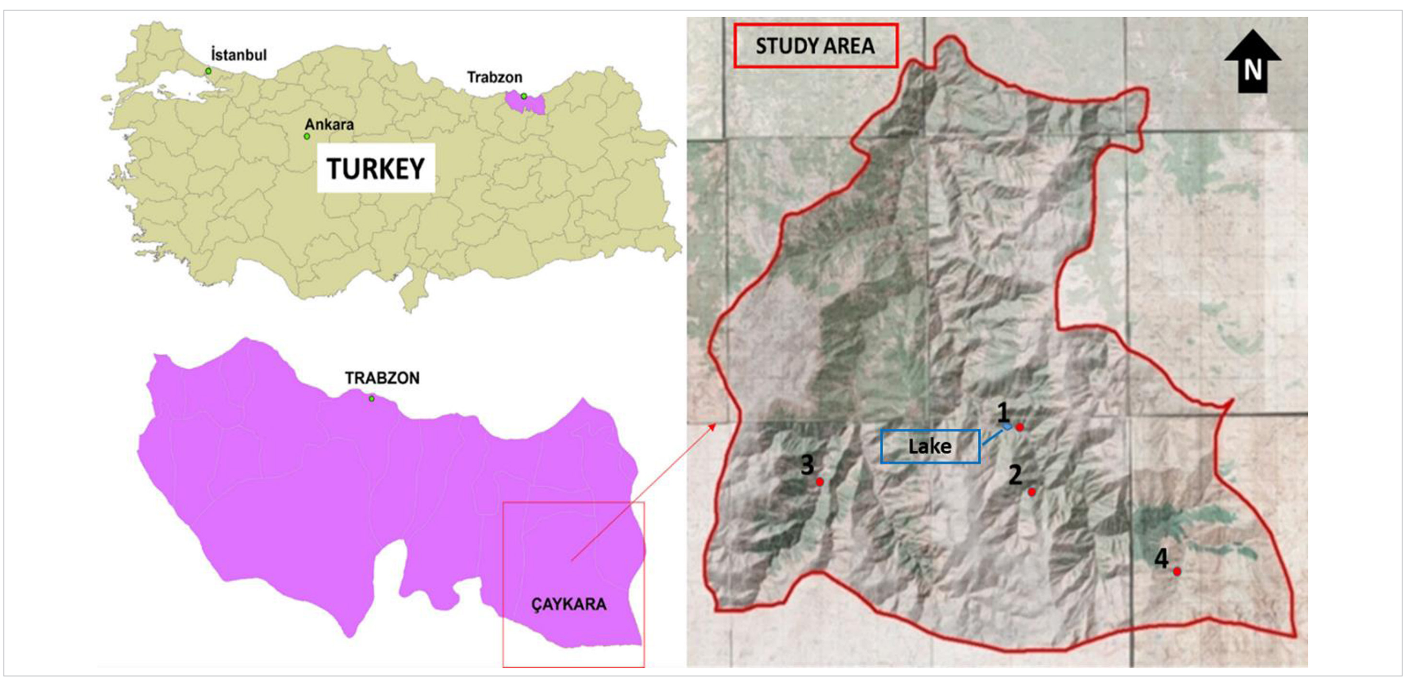

Figure 1.
Location of Çaykara District: (1) Uzungöl Nature Conservation Area, (2) Yaylaönü Village, (3) Uzuntarla Region, and (4) Demirkapı-Dursuoğlu Village.

Snow Avalanche Hazard Indication Mapping

In the present study, the GIS-based avalanche hazard indication map generation process (Figure 2) was divided into three basic stages: (1) determination of potential release zones, (2) determination of avalanche extent with 2D avalanche simulations, and (3) generation of an avalanche hazard indication map.

In the first stage, an algorithm developed by Bühler et al. (2013) was used to determine the potential release zones. This algorithm determines avalanche release zones depending on whether or not forests exist in the area. In the present study, potential release zones were determined considering the existence of forest stands providing a protective effect against snow avalanches. A digital map of forest stands (in vector format) was obtained from the Trabzon Regional Forest Service, converted to a raster format, and then used as an input file in the algorithm. However, this map was first reorganized into two classes ("0" and "1"), depending on the forest stand types attribute information in the database (crown closure, tree species, and pure or mixed distribution, and developmental stage). The criteria for the reclassification of the forest stand map were as follows: if forest stand types were equal to settlement or agricultural areas, open forest (gaps in forest areas), stony/erosional areas, both coniferous or broad-leaved forest stands with low crown closure (10–40%) including both pure or mixed broad-leaved tree species, young forest stands of less than 8 cm of DBH, and any type of degraded forests, the new class value was assigned as "0." Otherwise, the new class value for all remaining forest stand types was assigned as "1." In other words, the value "1" means forested areas considered in determining the potential release zones, whereas the value "0" means all types of land covers not considered. Reclassified forest stand types were then converted into a raster format with 10-m spatial resolution. As the main input of this algorithm, a digital elevation model (DEM), at a 10-m pixel resampling distance, was generated from the digital topographical map at a scale of 1/25000. Other parameters required for the determination of potential release zones included relevant topographic features such as curvature, slope, ruggedness, and elevation (Bühler et al., 2013). In the study, the curvature value was incorporated with the ruggedness value, and the ruggedness threshold was selected as 0.03, meaning that more concave slopes without ridges would be selected as starting zones. Minimum and maximum slope values were selected as 28° and 55°, respectively, and minimum elevation as 1000 m, as the lower point of the seasonal snow line for a long-term return interval (i.e., 100 years) observed at this altitude. The generated potential release zones had their final plausibility checked manually and, when necessary, edited by an expert.

In the second stage, for 2D numerical avalanche simulation, the same methodology was used with ELBA+ (Energy Line-Based Avalanche) software (Volk et al., 2015). The ELBA+ simulations require two parameters: the Coulomb friction (μ) and the velocity-squared dependent turbulent friction (ξ). In addition to these two parameters, release zones (m^2), release height (m), snow density in the release zone (kg/m^3), and DEM data were the necessary inputs for simulations, with entrainment and resistance areas being optional. The release heights of the simulations were taken as 150 cm for the assumed 100-year return period. Due to the high amount of snowfall in the study area, the entire extent of the avalanche was accepted as the entrainment range. The entrainment ratio was selected 25 cm, corresponding to the recurrent periods of 100 years. Turbulent friction was calculated as a function of flow height and roughness while the simulation was being run by the software. The Coulomb friction was selected as 0.26 in the release zone, 0.165 in the track, and 0.33 in the run-out zone. The cut-off value was chosen as 0.1 m which is the default for the ELBA+ software. In the third stage, for the formation of the avalanche hazard map from the ELBA+ results, the LSHM4ELBA+ (Large Scale Hazard Mapping for ELBA+) algorithm was used to form the hazard map for the study area (Aydın & Eker 2017a).

Determining and Mapping of FS-PPF

The present study also aimed to determine the FS-PPF against snow avalanches. These were actually forest stands situated inside the snow avalanche release zones having a specified forest structure in terms of crown closure, developmental stage, and composition of tree species. Thus, the FS-PPF were determined via the outputs of the algorithm used for establishing potential snow avalanche release zones. This algorithm enables release zones to be determined both with and

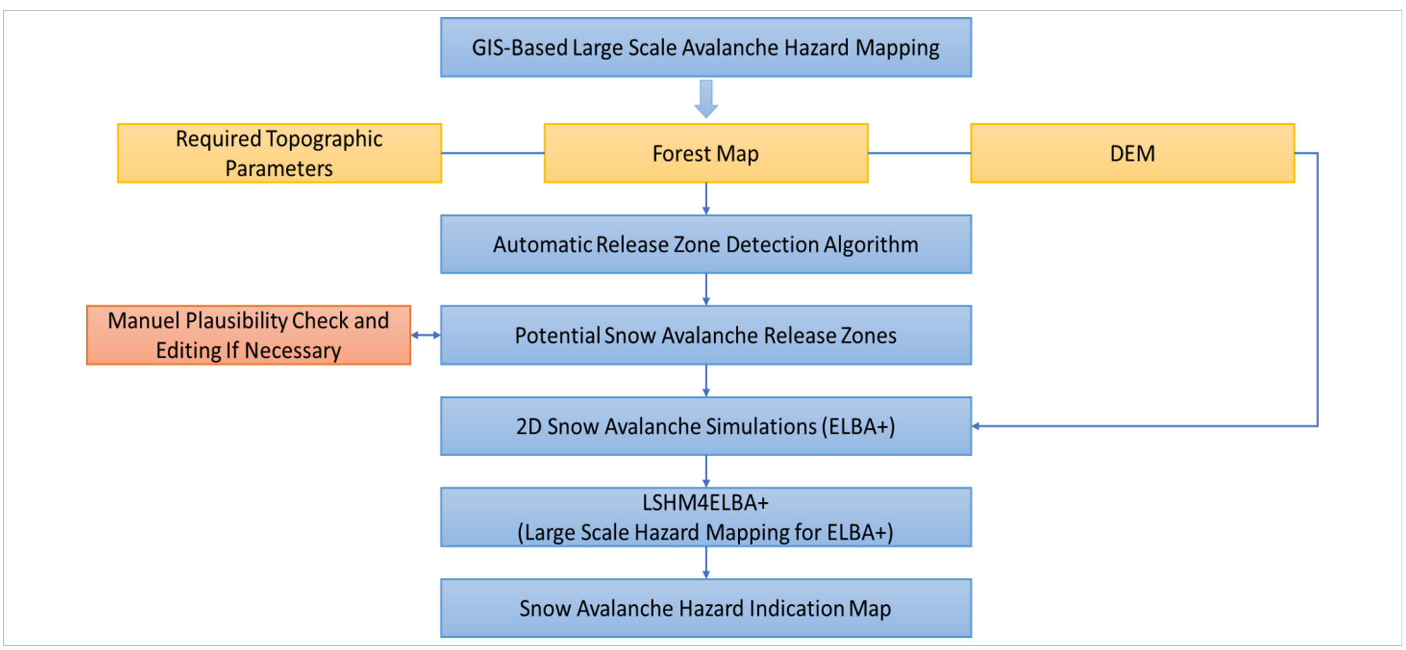

Figure 2.
Generation Process for GIS-Based Avalanche Hazard Indication Map.

without considering the existence of forests. First, the snow avalanche release zones were determined without considering forests and then mapped. Next, the snow avalanche release zones were determined considering the forests and then mapped according to the forest stand types, as explained in the previous section. Following this, the snow avalanche release zones considering the forests were removed from those not considering forests. The resulting vector data were then intersected with the stand maps to obtain the FS-PPF against snow avalanches. The workflow of this process is given in Figure 3. The resulting forest map was then classified in terms of degrees of protection against snow avalanches according to the forest stand type forms (tree species and crown closure). The degrees of protection were defined as five classes: high, moderate, moderate-low, low, and very low (Table 1). For the present study, ArcGIS 10.6 software was used for data preparation, analysis, and visualization.

Results and Discussion

Results of Snow Avalanche Hazard Indication Mapping

In the first, potential snow avalanche release zones were mapped by considering that forests existed in the region. The identification of potential release zones is not an easy task but is the precondition for hazard indication mapping. In the first automated approaches in delineating potential snow avalanche release zones, DEMs with quite coarse resolutions were used (i.e., 25–30 m) (Maggioni, 2005; Maggioni & Gruber, 2003; Maggioni et al., 2002). As Bühler et al. (2018b) stated, DEMs with higher resolution (1 to 10 m) enabled to the calculation of DEM derivatives such as ruggedness or curvature. These parameters are of major importance for avalanche release (van Herwijnen & Heierli, 2009; Vontobel, 2011). In the present study, DEM with 10 m resolution was used in delineating potential snow avalanche release zones. According to Bühler et al. (2013), the algorithm is able to identify most of the potential release zones; however, it should be kept in mind that this algorithm neglects weather and snowpack information in delineating potential release zones. As a result, in total, 5525 potential release zones covering 8446 ha (corresponding to 15% of the study area) were determined in the area. In addition, potential release zones were also determined without considering forests in the area. According to this, in total, 8506 release zones were determined in the study area with a total area of 18667 ha, which is two times larger than the release areas determined when considering the forests. The avalanche hazard indication map is depicted in Figure 4. According to this map, avalanche hazards cover an extent of 22088 ha in the study area. This means that 39% of the total area is vulnerable to an avalanche hazard. In the present study, avalanche hazard indication mapping was carried out by considering forests in the determination of potential snow avalanche release zones.

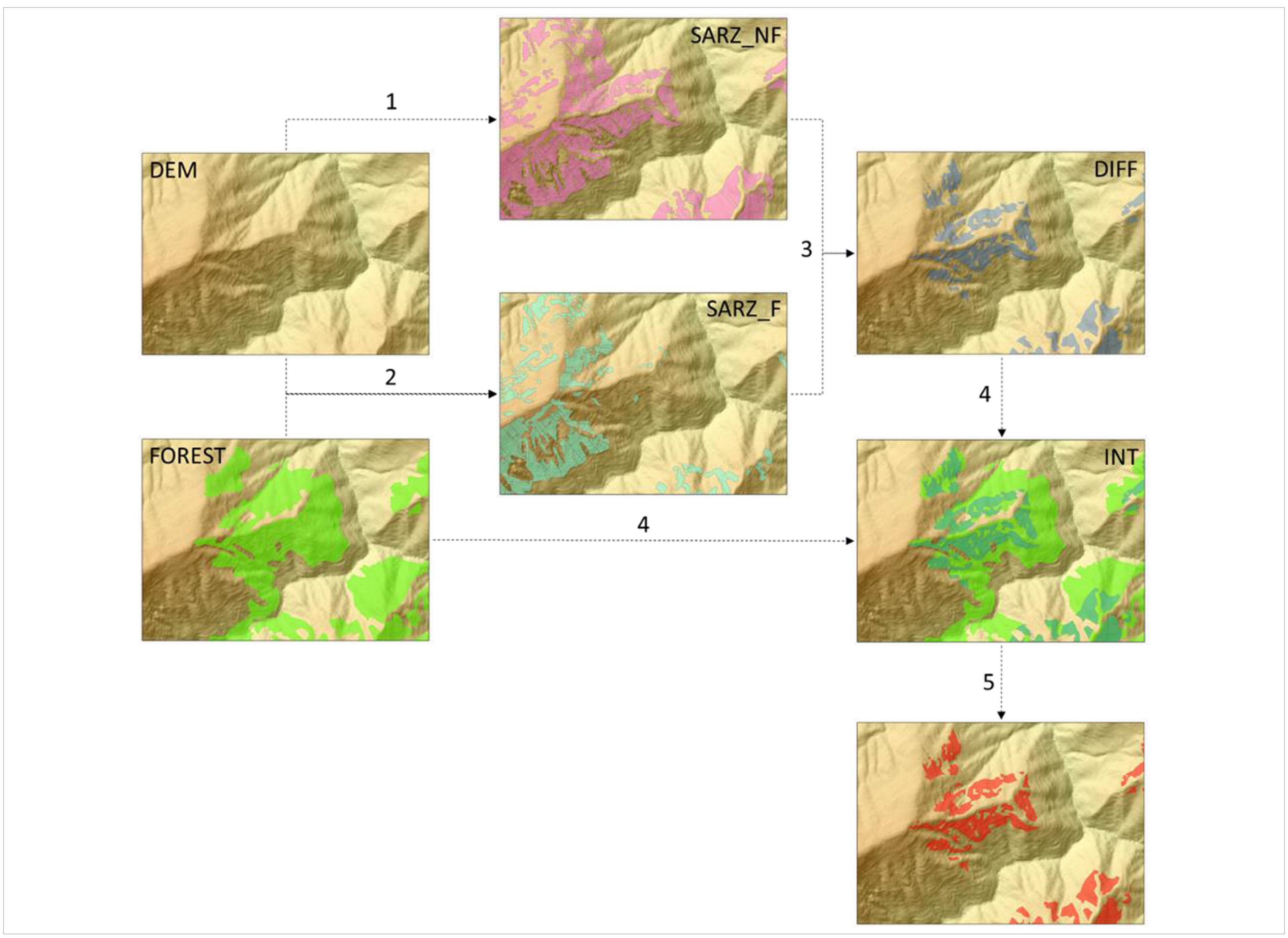

Figure 3.
Determination of FS-PPF: (1) Snow Avalanche Release Zones Determined Without Considering Forests (SARZ_NF), (2) Snow Avalanche Release Zones Determined Considering Forests (SARZ_F), (3) Removing SARZ_F From SARZ_NF (DIFF = SARZ_NF-SARZ_F), (4) Intersecting DIFF With FOREST Map (INT), and (5) Mapping of FS-PPF.

Table 1.
Criteria for Classifying the FS-PPF Protection Degree

		Coniferous Tree Species			Broad-Leaved Tree Species		
		I	II	III	IV	V	VI
Crown Closure (%)	10–40						
	40–70						
	70–100						
	High	Moderate	Moderate-Low	Low	Very low		

Note: I, IV: Pure stands.
II, V: Mixed coniferous/mixed broad-leaved stands.
III, VI: Mixed stands (coniferous/broad-leaved tree species predominant).

A similar approach in avalanche hazard indication mapping was applied by Issler et al. (2018) by taking into account both climatic conditions and forest cover to eliminate areas with very low release probability.

According to Bühler et al. (2013) stated, the best way to validate the results of the approach is to compare them with real avalanche events which are georeferenced accurately. As there are no official event documentation procedures and because the existing database-generated hazard indication map was overlapped only with known avalanche events in the area, the map was observed to be quite compatible with the locations of known avalanche events in Uzuntarla and Yaylaönü. This overlapping method provided valuable information about the validity of the generated snow avalanche hazard indication map. However, it should be kept in mind that these events are only very few records with accurate georeferencing. But it was the best data available to verify the results. The overlapped maps are given in Figures 5 and 6. When the snow avalanche hazard situation of Uzungöl was evaluated, many potential snow avalanche hazards were observed threatening the settlements around the lake (Figure 7).

Results of Determining and Mapping of FS-PPF
In addition to large-scale snow avalanche hazard indication mapping, the FS-PPF against snow avalanches were determined, classified into five protection degrees according to Table 1, and mapped (Figure 8). The resulting map showed, in total, 6629 ha of FS-PPF. In terms of protection, 72% of pure or mixed coniferous forests with higher than 70%

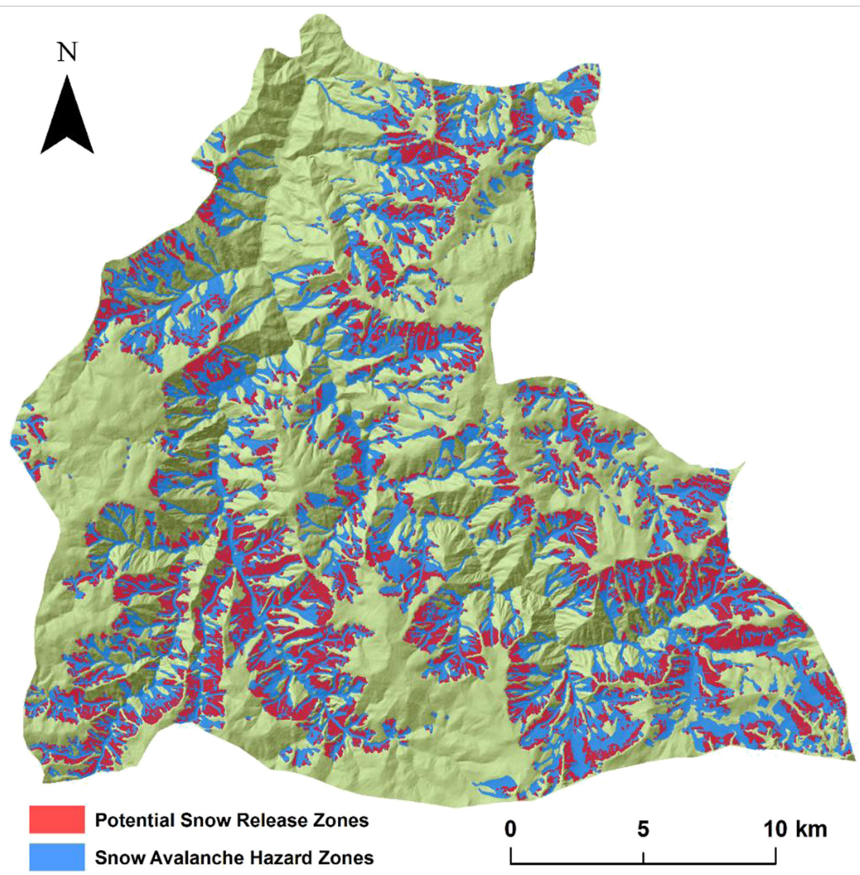

Figure 4.
Snow Avalanche Hazard Indication Map.

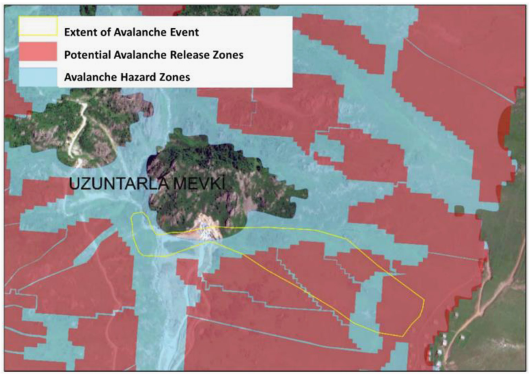

Figure 5.
Comparison of Avalanche Hazard Map With the Uzuntarla Avalanche (For More Detail, Aydın et al., 2015).

crown closure were classified as a high degree of protection. In addition, 18% of forest stands with higher than 70% crown closure were classified as a moderate protection degree, whereas 47% of forest stands with 40–70% crown closure were also classified as moderate. The forest stands that had a low protection degree covered a lower percentage (<10%) of the area. While 42% of the forest stands mapped had 40–70% crown closure, 37% had higher than 70% crown closure (Table 2, Figure 9). In addition, Table 3 and Figure 10 show the protection degree distribution of forests mapped at different elevations and slopes. Accordingly, the elevation values of the mapped protection forests varied between 1000 and 2358 m a.s.l. In terms of mean elevation values, the forests with a low degree of protection were located at lower elevations (1332 m a.s.l.) relative to the other protection degrees because the forest stand type forms included pure or mixed broad-leaved tree species. The forests with a very low protection degree were located at a wide range of elevations, ranging from 1000 to 2213 m a.s.l. because that class of protection degree included all types of forest stand forms with 10–40% crown closure. In terms of mean slope degree, all forest protection degree classes were located on slopes of greater than 33°. Schneebeli and Bebi (2004) also stated that avalanches in forests are released mostly on slopes greater than 30° as a function of the forest stand structures. It was observed that the mean slope inclination of forests with a protective function decreased from a high degree of protection to a low protection degree. This information is crucial in planning silvicultural operations with regard to treatment techniques and their costs. In terms of forest stand types, results showed that 54% of the FS-PPF against snow avalanches were of pure or mixed coniferous tree species, 24% of mixed coniferous and broad-leaved tree species, 11% of mixed broad-leaved and coniferous tree species, and 11% of pure or mixed broad-leaved tree species (Figure 11).

In the present study, the protection degree of the FS-PPF was categorized in five classes (from high to very low) considering the forms of forest stand types including information on crown closure and tree species and their distribution (pure or mixed). The protection degree classes of

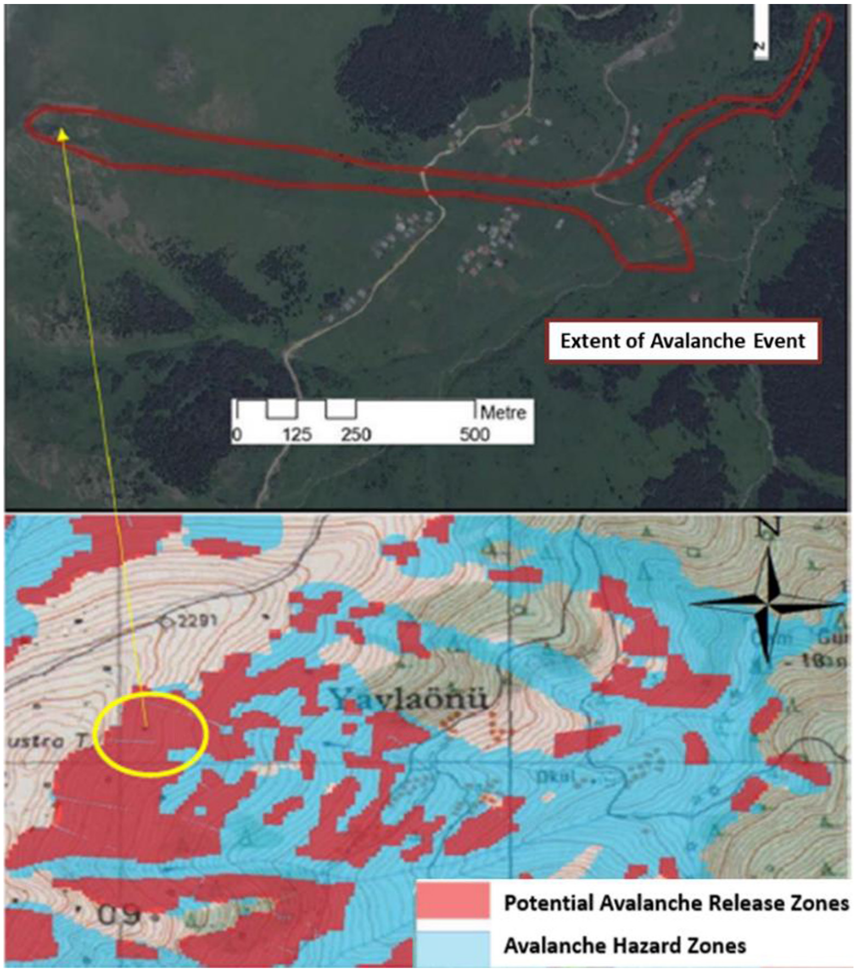

Figure 6.
Comparison of Avalanche Hazard Map With the Yaylaönü Avalanche of 1981 (For More Detail, Aydın et al., 2014).

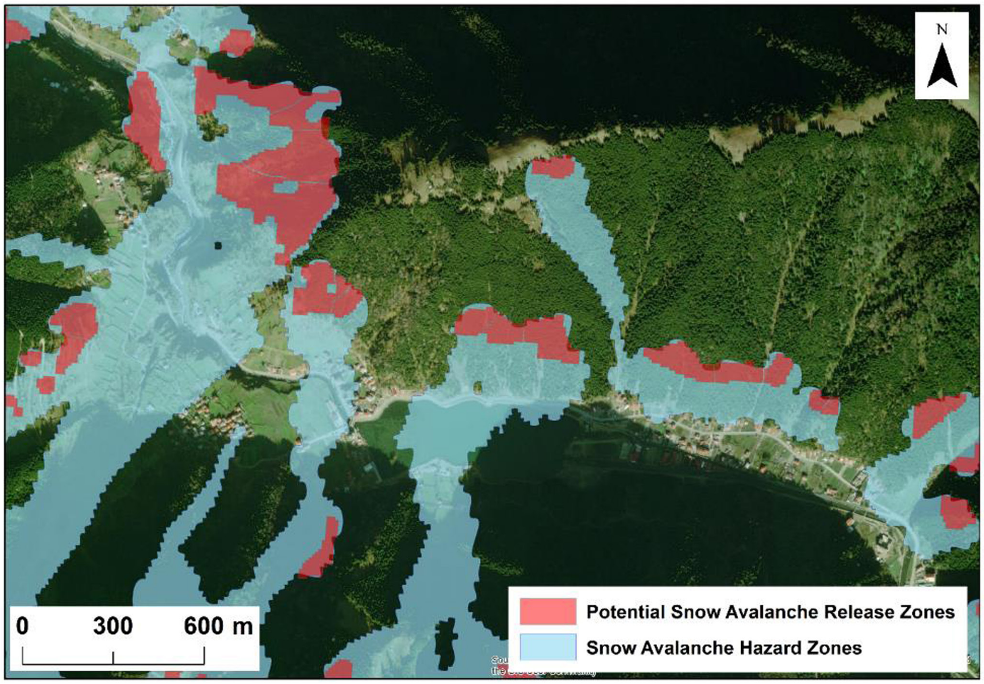

Figure 7.
Avalanche Hazard Situation of Uzungöl.

forest stands considered in this study, of course, can be modified and defined in different ways depending on the other criteria. Furthermore, the classification procedure proposed here did not include other forest parameters such as developmental stage, DBH, tree/stand height, stem density, distribution of tree types inside the forest stand, etc. Even if this classification procedure did not directly consider other forest parameters, some were considered indirectly. For example, the three classes of crown closure (%) in Turkey (i.e., 10–40%, 40–70%, and 70–100%) are defined as the proportion of a stand covered by the crowns of live trees having a DBH of greater than 8 cm. In addition, tree species were considered only as broad-leaved and coniferous. The attribute tables of digital forest stand maps used in Turkey do not include detailed information on tree number, stem density, tree or mean stand height, etc.; however, these details can be found in forest management plans. If such detailed information could be added to the attribute tables of the digital forest stand maps used in Turkey, a more comprehensive determination of the FS-PPF could be conducted. In this study, no field measurements of forest stand parameters were carried out. The aim was to determine the potential protective forest function using the fewest number of

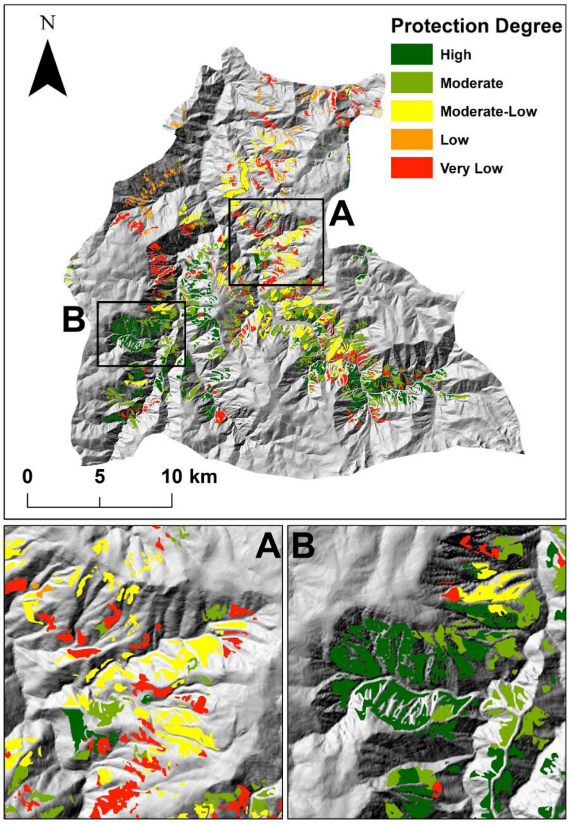

Figure 8.
FS-PPF Categorized in Five Protection Degree Classes.

Table 2.
Summary of FS-PPF

Protection Degree under Crown Closure	Area (ha)	%
10–40%	1403	21
Very Low	1403	100
40–70%	2807	42
Moderate	1313	47
Moderate-Low	1281	46
Low	213	7
70–100%	2419	37
High	1738	72
Moderate	424	17
Moderate-Low	121	5
Low	137	6
Total	6629	100

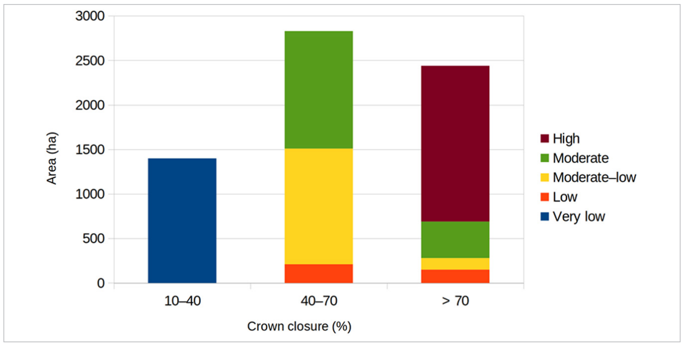

Figure 9.
Distribution of Protection Degree of Forest Stands Under Crown Closure (%).

forest parameters with available data in the fastest way possible. The proposed method allows the mapping of only the forest stands located inside potential snow avalanche release zones, and consequently, no information is given about the situation of forests located inside avalanche track or run-out zones. Further comprehensive research could be conducted to evaluate the interactions of snow avalanches with forest stands within the avalanche track or run-out zones.

Conclusions and Recommendations

In the present study, a GIS-based large-scale snow avalanche hazard indication map was generated for Çaykara District (NE Turkey) where snow avalanches are frequent events. For this purpose, avalanche release zones were first determined using an algorithm based on topographic parameters such as slope, elevation, ruggedness, etc. This algorithm also allowed us to assess whether the presence of forests could be effective in averting avalanches in the area. In the present study, potential release zones were determined with regard to forest stands having a specified structure. Avalanche hazard zones were then determined by running a 2D snow avalanche simulation with ELBA+. The hazard map produced in this way highlighted areas that could be vulnerable to avalanches and could be extremely useful in multiple applications, including the planning of new infrastructure. Over the last decade, crucial land-use changes have been observed resulting from both increases in the population (although this is not the case for the study area) and the transformation of the agriculture-based society to one that is service-based. Plans for future research could aim to evaluate the interaction of snow avalanche hazards with these land-use changes in the region that have been putting pressure on the forest areas.

In Turkey, since the first management plan in 1917, the forest management planning system has evolved in terms of management approaches, moving away from a conventional planning approach in which management objectives during the planning process were concentrated on silviculture and utilization of forest resources without consideration for forest values/functions. In Turkey, these include three main categories: economic, ecological, and social values/functions. Beginning in 1998 and continuing to the present, planning has taken a functional approach, in which forest management units are separated according to forest values including, in addition to the three main categories, many different functional sub-categories varying from timber production to the esthetic (Yolasığmaz, 2004 for details). According

Table 3.
Elevation and Slope Features of FS-PPF

Protection Degree Classes	Min Elevation (m)	Max Elevation (m)	Mean Elevation (m)	Min Slope (°)	Max Slope (°)	Mean Slope (°)
High	1019	2160	1664	26	51	36
Moderate	1000	2358	1678	26	49	35
Moderate-low	1000	2008	1481	27	56	34
Low	1002	2109	1332	27	48	33
Very low	1019	2212	1562	27	50	35

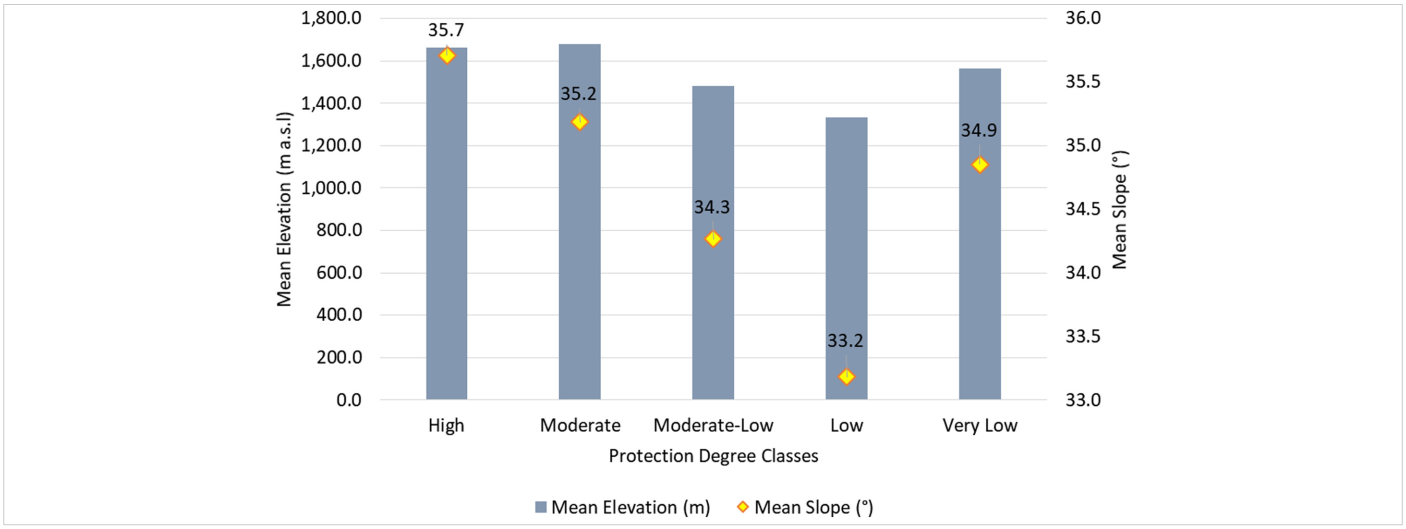

Figure 10.
Mean Elevation and Slope Degree of Forest Protection Degree Classes.

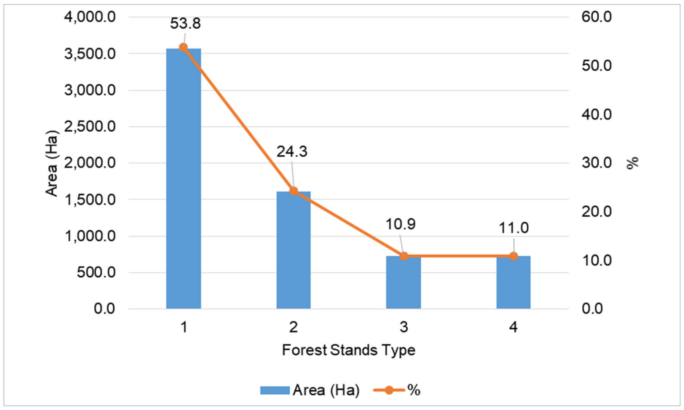

Figure 11.
Distribution of Forest Stand Types of FS-PPF Against Snow Avalanches: (1) Pure or Mixed Coniferous Tree Species, (2) Mixed Coniferous and Broad-Leaved Tree Species, (3) Mixed Broad-Leaved and Coniferous Tree Species, and (4) Pure or Mixed Broad-Leaved Tree Species.

to this functional planning approach in Turkey, the forest objective referred to as "avalanche prevention" is defined under the sub-category of "erosion prevention" in the main category of "ecological forest values". However, in past forest management plans in Turkey, no actual forest areas were known to have been planned with the objective of avalanche prevention. According to forest management regulations in Turkey, forest management plans are prepared using a participatory approach. In the planning of forest management, forest functions are determined via GIS and remote sensing techniques. Even if there is an avalanche prevention objective in the functional forest planning approach and even if the forest management regulations exist as the main road map for the forest manager, neither a snow avalanche hazard map nor a map produced for delineating the FS-PPF has been considered in preparing forest management plans in Turkey. The methodology of the present study is simple and acceptable for determining the FS-PPF against snow avalanches, and the resulting map could easily be integrated within management plans in Turkey. To date, no study in Turkey has proposed a method for determining the forests that are potentially protective against snow avalanches. However, Aydın and Eker (2017b) proposed a similar GIS-based method for mapping forests providing a protective function against rockfalls in Turkey.

When planning silvicultural operations in forest stands, the FS-PPF can also be used in making decisions depending on the protection degree. If a forest stand has a high degree of protection function against snow avalanches, silvicultural operations could be planned with the aim of avoiding the degradation of the actual structure of that forest stand. It should be kept in mind that these forest stands are located inside snow avalanche release zones and are mostly located at higher elevations (>1000 m a.s.l.) and on steep slopes (28°–55°). In other words, these stands are already located under harsh topographical conditions. If a forest stand has a moderate or moderate-low degree of protection, silvicultural operations could be planned to avoid degradation of the forest as well as to improve the structural characteristics of the forest stand to strengthen its potential protection function. If a forest stand has a low or very low degree of protection, then silvicultural operations could be planned to improve its long-term protection function by combining snow avalanche support structures (e.g., snow bridges, tripods, poles, etc.) depending on a benefit-cost analysis carried out if necessary. Of course, it should be noted that forest management/silvicultural operations and mitigation of snow avalanche hazards are both crucial and complex tasks. Thus, the output of this study could serve as a base map for a number of large-scale operations in forestry and snow avalanche studies.

Peer-review: Externally peer-reviewed.

Author Contributions: Concept – A.A.; Design – A.A.; Supervision – A.A., R.E.; Materials – R.E.; Data Collection and/or Processing – R.E., Y.B.O.; Analysis and/or Interpretation – A.A., R.E., Y.B.O.; Literature Search – R.E., Y.B.O.; Writing Manuscript – R.E.; Critical Review – A.A.

Conflict of Interest: The authors have no conflicts of interest to declare.

Financial Disclosure: The authors declared that this study has received no financial support.

References

- Atasoy, M. (2010). Monitoring land use changes in tourism centers with GIS: Uzungöl case study. *Scientific Research and Essays*, *5*(8), 790–798.
- Aydın, A., & Eker, R. (2017a). GIS-Based snow avalanche hazard mapping: Bayburt-Aşağı Dere catchment case. *Journal of Environmental Biology*, *38*, 937–943. [CrossRef]
- Aydın, A., & Eker, R. (2017b). Forest mapping against rockfalls on a regional scale in Inebolu of Turkey. *Journal of the Istanbul University Faculty of Forestry*, *67*(2), 136–149.
- Aydın, A., Bühler, Y., Christen, M., & Gürer, I. (2014). Avalanche situation in Turkey and back-calculation of selected events. *Natural Hazards and Earth System Sciences*, *14*(5), 1145–1154. [CrossRef]
- Aydın, A., Eker, R., & Odabaşı, Y. B. (2015). Analysis and back-calculation modelling of the 10 January 2015 Uzuntarla (Trabzon-Turkey) snow avalanche event. In *Proceeding of the International Conference on Engineering and Natural Science, 15–19 May* (pp. 632–639). Skopje: ICENS.
- Bartelt, P., & Stöckli, V. (2001). The influence of tree and branch fracture, overturning and debris entrainment on snow avalanche flow. *Annals of Glaciology*, *32*, 209–216. [CrossRef]
- Bebi, P., Kienast, F., & Schönenberger, W. (2001). Assessing structures in mountain forests as a basis for investigating the forests dynamics and protective function. *Forest Ecology and Management*, *145*(1–2), 3–14. [CrossRef]
- Bebi, P., Kulakowski, D., & Rixen, C. (2009). Snow avalanche disturbances in forest ecosystems—state of research and implications for management. *Forest Ecology and Management*, *257*(9), 1883–1892. [CrossRef]
- Brang, P., Schönenberger, W., Frehner, M., Schwitter, R., Thormann, J. J., & Wasser, B. (2006). Management of protection forests in the European Alps: An overview. *Forest Snow and Landscape Research*, *80*, 23–44.
- Brožová, N., Fischer, J., Bühler, Y., Bartelt, P., & Bebi, P. (2020). Determining forest parameters for avalanche simulation using remote sensing data. *Cold Regions Science and Technology*, *172*, 102976. [CrossRef]
- Brugnot, G. (1999). *SAME-Avalanche mapping, model validation and warning systems: Summary report* (p. 67). European Commision, European Environment and Climate Programme.
- Bühler, Y., Kumar, S., Veitinger, J., Christen, M., & Stoffel, A. (2013). Automated identification of potential snow avalanche release areas based on digital elevation models. *Natural Hazards and Earth System Sciences*, *13*(5), 1321–1335. [CrossRef]
- Bühler, Y., von Rickenbach, D., Christen, M., Margreth, S., Stoffel, L., Stoffel, A., & Kühne, R. (2018a). Linking modelled potential release areas with avalanche dynamic simulations: An automated approach for efficient avalanche hazard indication mapping. *International Snow Science Workshop*, Innsbruck, Austria: ISSW.
- Bühler, Y., von Rickenbach, D., Stoffel, A., Margreth, S., Stoffel, L., & Christen, M. (2018b). Automated snow avalanche release area delineation – validation of existing algorithms and proposition of a new object-based approach for large-scale hazard indication mapping. *Natural Hazards and Earth System Sciences*, *18*(12), 3235–3251. [CrossRef]
- Bulut, S., Günlü, A., & Keleş, S. (2016). Estimation of some stand parameters using Göktürk-2 satellite image. In *Proceedings of the 1st International Symposium of Forest Engineering and Technologies* (pp. 118–124). Bursa, Turkey.

- Casteller, A., Häfelfinger, T., Cortés Donoso, E. C., Podvin, K., Kulakowski, D., & Bebi, P. (2018). Assessing the interaction between mountain forests and snow avalanches at Nevados de Chillán, Chile, and its implications for ecosystem-based disaster risk reduction. *Natural Hazards and Earth System Sciences*, *18*(4), 1173–1186. [CrossRef]
- Coaz, J. (1881). *Die Lauinen der Schweizer Alpen*. Bern: Schmid-Franke & Cie. (in German)
- De Quervain, M. (1978). Wald und Lawinen. In *Proceedings of the IUFRO Seminar Mountain Forests and Avalanches (pp. 219–231), Davos, Switzerland*.
- Feistl, T., Bebi, P., Bühler, Y., Christen, M., Teich, M., & Bartelt, P. (2012). Stopping behaviour of snow avalanches in forests. In *Proceedings of the 2012 International Snow Science Workshop* (pp. 420–426). Anchorage, Alaska, USA: ISSW.
- Frehner, M., Schwitter, P., & Wasser, B. (2005). *Nachhaltigkeit und Erfolgskontrolle im Schutzwald. Wegleitung für Pflegemaßnahmen in Wäldern mit Schutzfunktion*. Bern: Swiss Agency for the Environment, Forests and Landscape (SAEFL). (in German)
- Frutiger, H. (1980). Swiss avalanche hazard maps. *Journal of Glaciology*, *26*(94), 518–519. [CrossRef]
- Gruber, U., & Baltensweiler, A. (2004). *SilvaProtect-CH. Birmensdorf, Schweiz: Eidg. Forschungsanstalt WSL*. (in German). https://nhess.copernicus.org/articles/18/3235/2018/#section10
- Hedstrom, N. R., & Pomeroy, J. W. (1998). Measurements and modeling of snow interception in the boreal forest. *Hydrological Processes*, *12*(10–11), 1611–1625. [CrossRef]
- In der Gand, H. (1978). Verteilung und Struktur der Schneedecke unter Waldbäumen und im Hochwald. *IUFRO Working Party on Snow and Avalanches* (pp. 98–119). Davos, Switzerland: International Seminar on Mountain Forests and Avalanches Federal Institute for Snow and Avalanche Research. (in German)
- Issler, D., Gauer, P., Gisnås, K. G., & Domaas, U. (2018). Approaches to including forest effects in avalanche hazard indication maps in Norway. *Geophysical Research Abstracts*, *20*, EGU2018-15869.
- Kangas, A., Jeffrey, H. G., & Scott, C. T. (2006). Chapter 1 – Introduction. In A. Kangas & M. Maltamo (Eds.). *Forest inventory: Methodology and applications* (pp. 3–13). Dordrecht, the Netherlands: Springer.
- Kayacan, B., Zengin, H., & Kadiogullari, A. I. (2016). Chapter 44 – Turkey. In C. Vidal, I. Alberdi, L. Hernandez & J. Redmond (Eds.), *National forest inventories: Assessment of wood availability and use* (pp. 807–827). Cham, Switzerland: Springer.
- LeMay, V., Maedel, J., & Coops, N. C. (2008). Estimating stand structural details using nearest neighbor analyses to link ground data, forest cover maps, and Landsat imagery. *Remote Sensing of Environment*, *112*(5), 2578–2591. [CrossRef]
- Maggioni, M. (2005). *Avalanche release areas and their influence on uncertainty in avalanche hazard mapping*, Zurich: University of Zurich UZH.
- Maggioni, M., & Gruber, U. (2003). The influence of topographic parameters on avalanche release dimension and frequency. *Cold Regions Science and Technology*, *37*(3), 407–419. [CrossRef]
- Maggioni, M., Gruber, U., & Stoffel, A. (2002). Definition and characterisation of potential avalanche release areas. *ESRI International User Conference 2002* (pp. 1161–1166). San Diego, USA.
- Margreth, S. (2004). Die Wirkung des Waldes bei Lawinen. *Swiss Federal Institute for Forest, Snow and Landscape Research, Birmensdorf, Switzerland* (pp. 21–26). Forum für Wissen. (in German)
- McClung, D. M. (2003). Magnitude and frequency of avalanches in relation to terrain and forest cover. *Arctic, Antarctic, and Alpine Research*, *35*(1), 82–90. [CrossRef]
- McClung, D. M., & Schaerer, P. (2006). *The avalanche handbook* (3rd edition). Mountaineers Books.
- Meyer-Grass, M. (1987). Waldlawinen: gefährdete Bestände, Massnahmen, Pflege des Gebirgswaldes. In N. Bischoff (Ed.), *Pflege des Gebirgswaldes: Leitfaden fur die Begrünung und forstliche Nutzung von Gebirgswäldern*. Berne, Switzerland: EDMZ. (in German)
- Montesi, J., Elder, K., Schmidt, R. A., & Davis, R. E. (2004). Sublimation of intercepted snow within a subalpine forest canopy at two elevations. *Journal of Hydrometeorology*, *5*(5), 763–773. [CrossRef]
- Monti, F., Alberti, R., Comin, P., Wolynski, A., & Buhler, Y. (2018). Automated identification of forest with protective function against snow avalanches in the Trento Province (Italy). *International Snow Science Workshop* (pp. 731–735). Innsbruck, Austria: ISSW.
- Motta, R. (1995). I lariceti delle Alpi *occidentali*: Un *Problema ecologico selvicolturale*. *Silvae Pedemontis*, *1*, 7–16. (In Italian).
- Nairz, P., Mears, A., Sauermoser, S., Gabl, K., Stoffel, M., & Margreth, S. (2015). Avalanches: Evolution and impact. In F. Rudolf-Miklau, S. Sauermoser & A. Mears (Eds.), *The technical avalanche protection handbook*. Berlin: Wilhelm Ernst and Sohn.
- Oller, P., Janeras, M., Costa, O., García-Sellés, C., Muntán, E., Martí, G., & Martínez, P. (2013). Avalanche hazard mapping plan for the Catalan Pyrenees. *International Snow Science Workshop* (pp. 604–610). Grenoble: Chamonix Mont-Blancn.
- Pomeroy, J. W., & Brun, E. (2001). Physical properties of snow. In H. G. Jones, J. W. Pomeroy, D. A. Walker & R. W. Hoham (Eds.), *Snow ecology*. Cambridge: Cambridge University Press.
- Rudolf-Miklau, F., Sauermoser, S., & Mears, A. (2015). *The technical avalanche protection handbook*. Berlin: Wilhelm Ernst and Sohn.
- Saeki, M., & Matsuoka, H. (1969). *Snow-buried young forest trees growing on steep slopes, Seppyo*, *31* (pp. 19–23). Japanese Society of Snow and Ice.
- Schneebeli, M., & Bebi, P. (2004). Snow and avalanche control. In J. Burley, J. Evans & J. A. Youngquist (Eds.), *Encyclopedia of Forest sciences* (pp. 397–402). Elsevier, Amsterdam.
- Schneebeli, M., & Meyer-Grass, M. (1993). Avalanche starting zones below the timber line—structure of forest. In *Proceedings of the International Snow Science Workshop,* 4–8 October, 1992 (pp. 176–181). Breckenridge, Colorado.
- Schönenberger, W., & Brang, P. (2004). Silviculture in mountain forests. In J. Burley, J. Evans & J. A. Youngquist (Eds.), *Encyclopedia of Forest Sciences* (pp. 1085–1094). Elsevier.
- Stethem, C., Jamieson, B., Schaerer, P., Liverman, D., Germain, D., & Walker, S. (2003). Snow avalanche hazard in Canada: A review. *Natural Hazards*, *28*, 487–515. [CrossRef]
- Teich, M., & Bebi, P. (2009). Evaluating the benefit of avalanche protection forest with GIS-based risk analyses: A case study in Switzerland. *Forest Ecology and Management*, *257*(9), 1910–1919. [CrossRef]
- Teich, M., Giunta, A. D., Hagenmuller, P., Bebi, P., Schneebeli, M., & Jenkins, M. J. (2019). Effects of bark beetle attacks on forest snowpack and avalanche formation – implications for protection forest management. *Forest Ecology and Management*, *438*, 186–203. [CrossRef]
- Teich, M., Marty, C., Gollut, C., Grêt-Regamey, A., & Bebi, P. (2012). Snow and weather conditions associated with avalanche releases in forests: Rare situations with decreasing trends during the last 41years. *Cold Regions Science and Technology*, 83–84, 77–88. [CrossRef]
- van Herwijnen, A., & Heierli, J. (2009). Measurement of crack-face friction in collapsed weak snow layers. *Geophysical Research Letters*, *36*(23), 1–5. [CrossRef]
- Vatandaşlar, C., & Zeybek, M. (2020). Application of handheld laser scanning technology for forest inventory purposes in the NE Turkey. *Turkish Journal of Agriculture and Forestry*, *44*(3), 229–242. [CrossRef]
- Vidal, C., Sallnas, O., Redmond, J., Alberdi, I., Barreiro, S. et al. (2016). Chapter 1 - Introduction. In C. Vidal, I. Alberdi, L. Hernandez & J. Redmond (Eds.). *National forest inventories: Assessment of wood availability and use* (pp. 1–25). Cham, Switzerland: Springer.
- Viglietti, D., Letey, S., Motta, R., Maggioni, M., & Freppaz, M. (2010). Snow avalanche release in forest ecosystems: A case study in the Aosta Valley Region (NW-Italy). *Cold Regions Science and Technology*, *64*(2), 167–173. [CrossRef]
- Volk, G., Aydın, A., & Eker, R. (2015). Avalanche control with mitigation measures: a case study from Karaçam-Trabzon (Turkey). *European Journal of Forest Engineering*, *1*(2), 61–68.
- Vontobel, I. (2011). *Geländeanalysen von Unfalllawinen*. MS, Department of Geography, University of Zurich.
- Yolasığmaz, H. A. (2004). *The concept and the implementation of forest ecosystem management (A case study of Artvin Planning Unit)* [PhD Thesis]. Trabzon, Turkey: Karadeniz Technical University Faculty of Forestry.