Izvirni znanstveni članek / Original scientific paper

RECONSTRUCTION OF ROCKFALL ACTIVITY THROUGH DENDROGEOMORPHOLOGY AND A SCAR-COUNTING APPROACH: A STUDY IN A BEECH FOREST STAND IN THE TRENTA VALLEY (SLOVENIAN ALPS)

REKONSTRUKCIJA PODORNE AKTIVNOSTI Z UPORABO DENDROGEOMORFOLOGIJE IN METODE ŠTETJA POŠKODB: PRIMER BUKOVIH GOZDOV V DOLINI TRENTE (SLOVENSKE ALPE)

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ABSTRACT

Trees represent an important archive that can be used to reconstruct the spatial and temporal patterns of rockfall events. Rockfall impacts can be recorded in the form of anomalies in tree rings and impact scars on the tree stem. In this paper we demonstrate the use of an approach based on counting scars for reconstructing the frequency and spatial pattern of past rockfalls. The approach was applied by counting the visible scars on the stem surface of 52 European beech trees (*Fagus sylvatica* L.) in the area of the Trenta Valley, Slovenia. The average number of impacts per trees was 7, and the impacts were mostly classified as old, indicating reduced rockfall activity in recent years. The average recurrence interval was 31.8 years, which was reduced by 1.2 years by the application of the conditional impact probability. The spatial pattern of rockfall impacts shows that rockfall activity is higher in the middle part of the studied slope.

Key words: rockfall, natural hazards, dendrogeomorphology, tree rings, stem scars, recurrence interval

IZVLEČEK

Drevesa so pomemben arhiv podatkov o preteklih dogodkih za rekonstrukcijo prostorske in časovne aktivnosti skalnih podorov, saj beležijo vplive skalnih podorov z anomalijami v rasti drevesnih branik ali prek vizualnih poškodb, vidnih na površju debel. V prispevku je predstavljena metodologija preučevanja skalnih podorov z analizo vidnih poškodb na deblu 52 dreves navadne bukve (*Fagus sylvatica* L.) na območju doline Trente v Sloveniji. Na podlagi analize smo ugotovili, da je povprečno število poškodb na posamezno drevo 7 ter da večinoma spadajo v kategorijo starih poškodb, kar kaže na manjšo aktivnost skalnih podorov v zadnjih letih. Povprečna povratna doba pojavljanja skalnih podorov je znašala 31,8 let; le-ta pa se skrajša za 1,2 leta, če upoštevamo pogojno verjetnost vpliva, da skale lahko zgrešijo drevesa. Prostorsko pojavljanje skalnih podorov kaže na večjo aktivnost v osrednjem delu preučevanega pobočja.

Ključne besede: skalni podori, naravne nevarnosti, dendrogeomorfologija, drevesne branike, poškodbe debla, povratna doba

GDK 384+585(497.4Trenta)(045)=111
DOI 10.20315/ASetL.121.2

Prispelo / Received: 3. 9. 2019
Sprejeto / Accepted: 8. 1. 2020

1 INTRODUCTION

1 UVOD

Rockfall is one of the most common geomorphological processes, especially in mountainous regions (Stoffel et al., 2006), and occurs when rock blocks are detached from a vertical cliff (Ribičič, 1999), followed by the rapid down-slope movement of rocks via free falling, bouncing, rolling and sliding (Varnes, 1978). An active rockfall slope consists of three main parts (Dorren et al., 2007): i) the rockfall source (release) area, ii) the rockfall transit (propagation) area and iii) the rockfall deposit area. Rockfall release areas represent steep rock faces that consist of hard and erosion resistant rocks (Dorren et al., 2007) and are usually characterized by specific geological conditions (e.g. bedding planes, joints and fractures, orientation of discontinuities, etc.) (Ribičič, 1999). The transit area lies between the source and deposit areas. Rocks in the transit area are in motion and achieve the highest kinetic energies and jump heights, while deposit areas represent areas where most rocks stop moving (Dorren et al., 2007). Rockfall can be categorized as a rapid slope process that often occurs suddenly without any prior signs that would indicate the rockfall event. In the downslope movement phase, rocks can achieve great kinetic energies, meaning that they can travel long distances and potentially pose a risk to settled areas (Cruden and Varnes, 1996). Even though rockfalls constitute a lower economic risk compared to large-scale landslides, they can cause a similar number of fatalities at the same order of magnitude as other landslide types (Hoek, 2000; Budetta, 2004). The reason for this is that when a rockfall occurs, there is practically no time for evacuation and other protective measures that could reduce harm to buildings, infrastructure and people (Ferrari et al., 2016). In Slovenia, rockfalls most often occur in the Alpine region (Slovenian Alps) and in other hilly terrain (Ribičič and Vidrih, 1998; Zorn, 2002; Mikoš et al., 2006; Ribičič, 2010). The areas that are at highest risk of rockfalls in Slovenia are gorges with vertical slopes, which are most often composed of limestone, and in areas at the contact point between limestones and clastic rocks (Petje et al., 2005).

Dendrogeomorphology is the analysis of geomorphic processes through the study of growth anomalies in tree rings (Alestalo, 1971). Dendrogeomorphic research is based on the "process-event-response" concept (Shroder, 1978), where the "process" is represented by any geomorphic agent (e.g. rockfall, landslide, avalanche, etc.). An individual geomorphic "event" is an event that affects a tree and results in a range of growth "responses". Tree-ring studies can further our understanding of the nature, magnitude and frequency of rockfalls in both space and time, and can possibly help us to mitigate future impacts (Stoffel, 2006; Stoffel and Perret, 2006). Past rockfall events are in many cases absent in documentary records, especially if they occurred in non-settled areas. This missing information about the historical hazard and frequency of rockfalls can be obtained from tree rings, which are often referred to as natural archives or "silent witnesses" (Stoffel et al., 2010).

Tree-ring records can provide data going back several centuries and can be used for dating historical rockfall events with annual and sub-annual resolution (Stoffel et. al., 2010). Tree-ring analysis can contribute significantly in the following areas (e.g. Stoffel et al., 2005; Perret et al., 2006; Stoffel, 2006; Stoffel and Perret, 2006; Luckman, 2008; Ciabocco et al., 2009; Lundström et al., 2009; Moya et al., 2010a; Schneuwly, 2010; Stoffel et al., 2010; Guzzeti and Reichenbach, 2010; Šilhán et al., 2013): identifying and dating historical failure events, reconstructing long time series of rockfall events, determining the rates and spatial distribution of rockfall activity, investigating the seasonal variation of rockfall occurrences, providing long-term statistics for the geometry of rockfall trajectories in an area, determining the impact probability of rockfall on trees and fostering our understanding of the protective role of forests.

Dendrogeomorphic methods have mainly been used for reconstructing past rockfall activity based on the identification of growth disturbances recorded in tree-ring series after mechanical disturbance caused by rockfall impacts on trees (see references in the previous paragraph). This approach can provide time series data with high temporal precision of past rockfall events; however, it is a labour-intensive and time-consuming approach that is consequently not appropriate for large-scale rockfall analyses (Trappmann and Stoffel, 2013, 2015). The majority of tree-ring analyses use conifers for reconstructing rockfall activity since the wood of broadleaved tree species has a more complex anatomical structure that makes tree-ring analyses more challenging (Trappman in Stoffel, 2013). Conifers also form traumatic resin ducts (e.g. *Picea* spp., *Larix* spp., *Pinus* spp.; Wimmer et al., 1999 after Moya et al., 2010b), and in combination (Stoffel and Perret, 2006; Trappmann et al., 2013) with growth disturbances such as abrupt growth suppression, the presence of callus tissue, eccentric growth, the formation of reaction wood and abrupt growth release, up to 70 % of hidden rockfall scars can be identified (Perret et al., 2006). Broadleaves do not form traumatic resin ducts; therefore, the identification of rockfall activity can only be done through examining growth suppression or release (Šilhán et al., 2011). On the other hand, broadleaved tree species such as *Fagus sylvatica* L. have smooth and thin bark that is easily damaged by rockfall impact. Moreover, *F. sylvatica* lacks the ability to renew its bark ("peeling") and thus cannot mask rockfall injuries, making it an ideal species for documenting long-term past rockfall activity (Stoffel and Perret, 2006; Moya et al., 2010b; Šilhán et al., 2011; Trappmann and Stoffel, 2013).

Therefore, in the past decade a new approach for analysing rockfall activity has been developed that is based on counting externally visible scars (injuries) caused by rockfall impacts on tree stems. This approach was first introduced by Trappmann and Stoffel (2013), who used it to calculate rockfall return periods for *Picea abies* Karst. and *F. sylvatica* at a study site in Tyrol, Austria. The approach has most commonly been used at research sites in Switzerland and France, e.g. in the Swiss Alps by Corona et al. (2013), Trappmann et al. (2014), Morel et al. (2015) and Trappmann and Stoffel (2015), and in the French Alps by Favillier et al. (2015, 2017), Corona et al. (2017) and Mainieri et al. (2019). There is also one study from Mexico (Franco-Ramos et al., 2017). The scar-counting approach has been used for identifying the number of injuries and calculating rockfall frequencies and rockfall recurrence intervals in the following tree species: *Larix decidua* Mill., *Betula pendula* Roth., *Corylus avellana* L., *Fraxinus* sp., *Sorbus aria* (L.) Crantz., *Populus tremula* L., *Picea abies* Karst., *Fraxinus exelsior* L., *Salix caprea* L., *Acer pseudoplatanus* L., *Alnus incana* (L.) Moench, *Sorbus aucuparia* L., *Prunus avium* L. and *Pinus hartwegii* Lindl.

Compared with classical tree-ring approaches, the scar-counting approach has been demonstrated to be less precise, but good enough to allow the spatial quantification of rockfall activity while requiring much less time and effort (Trappmann and Stoffel, 2013). In Slovenia, the use of dendrogeomorphological methods has become more common in the study of different slope mass movement processes in the last few years (e.g. Novak et al., 2018; Oven et al., 2019; Konjar, 2019). However, none of the Slovenian studies have focused on rockfalls in particular or on using a methodology based on counting scars for reconstructing rockfall activity.

Therefore, the purpose of this paper is to present the scar-counting method for estimating and mapping rockfall recurrence intervals based on counting visible scars on the stem surface of *F. sylvatica*, following the approach proposed by Trappmann and Stoffel (2013). In this study we analyzed the spatial distribution of rockfall activity based on the locations of scars on individual tree stems, calculated recurrence intervals at the level of individual trees and adjusted the recurrence intervals according to conditional impact probability (CIP), which was first introduced by Moya et al. (2010b).

2 STUDY SITE

2 OBMOČJE PREUČEVANJA

The study site is located in the Trenta Valley (46°24’21’’ N, 13°43’21’’ E, 901–945 m a.s.l.) in Triglav National Park in the Julian Alps (Figure 1A). The site was chosen since it is highly susceptible to rockfall activity and located next to a larger rockfall. Rockfalls originate from a ~10–20 m high north-facing rock cliff (average slope 40°), situated in the forest, consisting of layered to massive limestone and dolomite (Carnian) (Jurkovšek, 1985). Limestone passes into dolomite in the vertical and lateral direction. In the geotectonic sense, the area is part of the Southern Alps and part of the Julian Alps overthrust (Jurkovšek, 1987; Placer, 2008). The dominant direction of the fractures is trans-

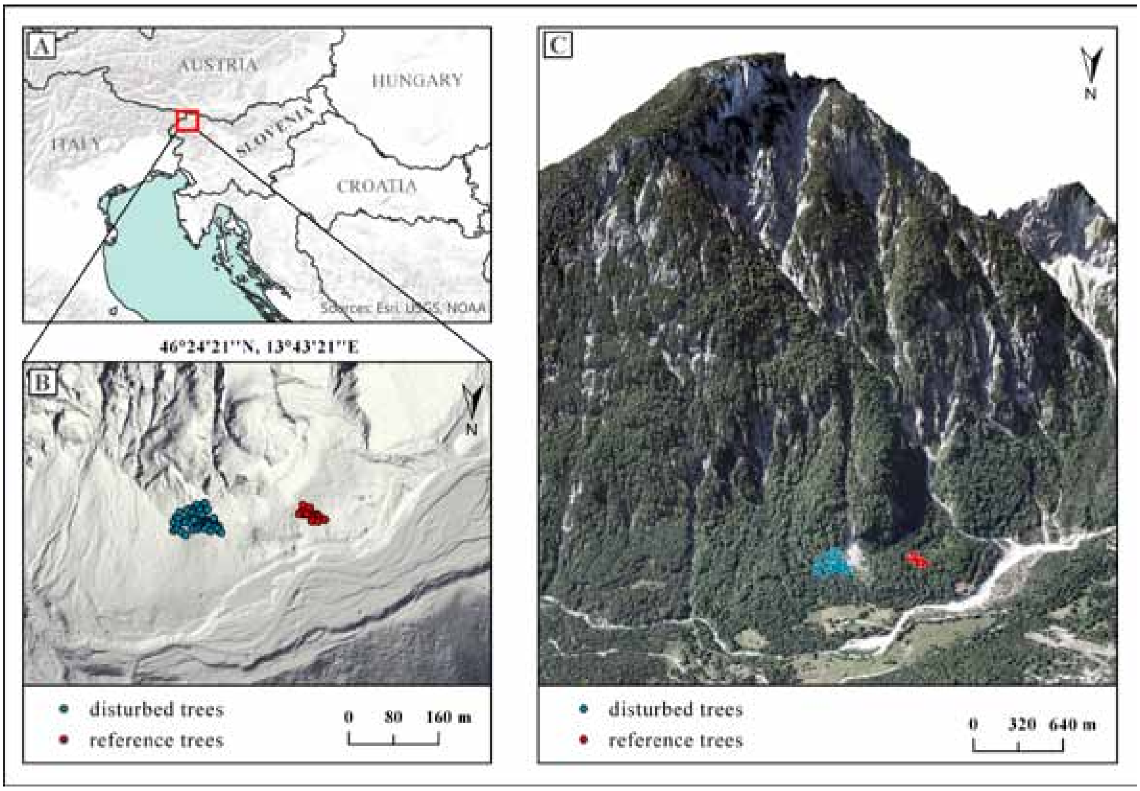

Fig. 1: A) The study site is located in the Trenta Valley in the northwestern part of Slovenia (Julian Alps). Maps B and C indicate the position of the study area and include the locations of disturbed and reference (undisturbed) trees.

Slika 1: A) Območje preučevanja leži v dolini Trente v severozahodnem delu Slovenije (Julijske Alpe). Karti B in C prikazujeta lokacijo preučevanja z označenimi poškodovanimi drevesi in referenčnimi (nepoškodovanimi) drevesi.

versal Dinaric (NE-SW), and also in the Dinaric direction (NW-SE) (Zupan Hajna et al., 2010). The study site is located directly below a cliff and is characterized by a 66 m long slope with maximum and average slope values of 51° and 26°, respectively. The volume of deposited rocks on the slope varies from a few dm^3 up to a maximum of 1 m^3. The study site encompasses an area of 0.6 ha and is covered by the *Anemono trifoliae-Fagetum* forest community (Čarni et al., 2002). In this area *F. sylvatica* is the main tree species, although individual *Larix decidua* Mill. trees are also present. There is no record of other geomorphic processes (e.g. avalanches, debris flows) occurring on this slope, meaning that the scars on the trees are due to rockfall activity.

3 MATERIALS AND METHODS
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3.1 Selection of the sampled trees and the scar-counting approach
3.1 Izbira vzorčenih dreves in štetje vidnih poškodb

On the selected plot, 52 live *F. sylvatica* trees with a diameter at breast height (DBH) larger than 5 cm were sampled (Figure 1B, C). These trees had visible scars (injuries) due to rockfalls and were marked as disturbed trees. Since disturbed trees often have missing and false rings which make them difficult to cross-date, 20 trees that were not injured by rockfalls or other natural disturbances (reference trees - undisturbed), and that experienced growth conditions similar to that of the disturbed trees, were sampled in order to cross-date and determine the correct age of the disturbed trees. The position of each tree was determined using a high-precision GNSS receiver (± 100 cm), and afterwards the locations were imported as geo-locations in the ArcGIS Pro 2.3.3. (2019) geographical information system (GIS). For each tree the following attributes were collected: DBH, social status of the tree, the number and age of scars, and the location and height of scars on the stem.

Scars were recorded and categorized into three age groups (Trappmann and Stoffel, 2013): fresh, medium and old (Figure 2). Scars categorized as fresh were identified based on their colour and the presence of chipped bark or injured wood. Medium-aged scars were identified as healing wounds that were in the process of overgrowing the injury, but not yet closed, while old scars were identified as injuries that had already overgrown. Additionally, the location and height of scars on the bark of individual trees were recorded. In order to avoid misclassifying scars that could have been caused by other injuries (e.g. woodpecker damage, branches or falling neighbouring trees), vertically elongated scars and scars smaller than 3 cm were not recorded (e.g. Perret et al., 2006; Trappmann and Stoffel, 2013). In order to determine the age of each tree, one increment core per tree was extracted on the undisturbed downslope side of the tree as close to the ground as possible. Samples were analysed and data processed following standard dendrochronological procedures (Bräker, 2002). The height and position of each scar on individual tree trunks were used for calculating the average rockfall impact height.

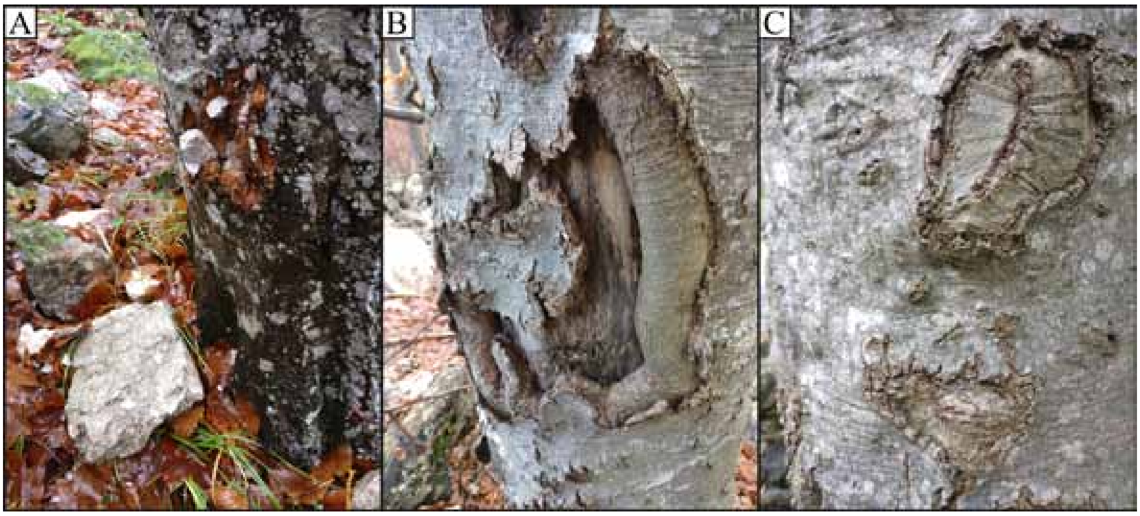

Fig. 2: Examples of scar age classes: A) fresh scar - wound closure has not begun, B) medium-aged scar - wound is in the process of becoming overgrown and C) old scar - wound is completely overgrown. Scar age is determined visually.

Slika 2: Primeri kategorij poškodb na drevesih: A) sveža poškodba - proces celjenja oz. zapiranja poškodbe se še ni pričel, B) srednje stara poškodba - poškodba v procesu zaraščanja, in C) stara poškodba - v celoti zarasla poškodba. Starost poškodb je ocenjena vizualno.

3.2 Calculation of the recurrence interval of individual rockfall impacts

3.2 Izračun povratnih dob pojavljanja skalnih podorov

In dendrogeomorphology the recurrence interval (*Ri*) represents the average time passing between two successive impacts at a specific point - the surface of the individual tree on the slope. It is calculated as follows (Trappmann and Stoffel, 2013):

$$Ri = \frac{A_t}{Sc_t} \qquad (1)$$

where *Ri* represents the recurrence interval, A_t represents the age of each tree as derived from dendrometric assessment and tree-ring counting, and Sc_t represents the number of scars that were visually identified on each stem *t*.

Recurrence intervals were visualized using a kriging model in ArcGIS Pro 2.3.3 (2019). Kriging is a geostatistical method that predicts spatial phenomenon at non sampled locations from an estimated random function (Loquin and Dubois, 2010). It uses a semivariogram to determine unknown values, and based on the semivariogram, optimal values are assigned to known values in order to calculate unknown values (Singh and Verma, 2019). The variogram changes with distance, and the weights depend on the known sample distance (Isaaks and Srivastava, 1990). The general equation of kriging is (Isaaks and Srivastava, 1990):

$$Z\ (s) = \mu\ (s) + \varepsilon'\ (s) \qquad (2)$$

where Z (s) is the variable of interest, μ (s) is a deterministic trend and ε' (s) is a random, auto correlated errors form that indicates the location (X, Y). Based on different definitions of μ (s), kriging methods are divided into the following types (Cressie, 1993): ordinary kriging, simple kriging, universal kriging, disjunctive kriging and indicator kriging.

Ordinary kriging is most commonly viewed as the application of statistics to study spatially distributed data (Loquin and Dubois, 2010), and it is an estimation of a technique called the Best Linear Unbaised Estimator (BLUE) (Cressie, 1993). In dendrogeomorphology studies of rockfalls, ordinary spherical kriging has been used for calculating rockfall return periods (e.g. Stoffel et al., 2005, 2011; Trappmann and Stoffel, 2013; Corona et al., 2013; Franco-Ramos et al., 2017). Therefore, the recurrence intervals were visualized for individual tree locations and spatially interpolated using the ordinary spherical kriging model.

3.3 Conditional impact probability

3.3 Pogojna verjetnost vpliva skale na drevo

The conditional impact probability approach (CIP) provides an estimate of the likelihood of rockfalls missing tree trunks (Moya et al., 2010b). The assessment of CIP depends on the forest parameters selected (stand density, tree location, DBH) and the rockfall event (volume of rocks). The CIP is based on the following simplified assumptions (Moya et al., 2010b, Favillier et al., 2017): i) the direction of falling rocks is assumed to be in a straight line and changes in direction due to rock impact on surfaces/trees do not influence the CIP since it measures the probability of rocks impacting trees, ii) trees are only represented by the stem via a circle in the horizontal plane and iii) changes in trunk diameter with height and age are insignificant for CIP estimation.

In the CIP concept (Figure 3; summarized based on Favillier et al., 2017) each tree is surrounded by a "circle of impact" which covers a certain part of the slope and thus reduces the space for rocks passing through the forest without impacting individual trees. The "circle of impact" therefore determines the probability of rock impacting the tree. A tree will be impacted by a falling rock if its trajectory is closer to the stem than half of its diameter (ø). The "circle of impact" is expressed as a circular area around each tree with a diameter defined by the tree's DBH and rock diameter (ø). The total length of impact circles (L_{IC}) (area that is covered by the trees) represents the sum of the impact circles from individual trees. Therefore, CIP is expressed as a fraction of the lengths as:

$$CIP = \frac{L_{IC}}{L_{plot}} \qquad (3)$$

where L_{IC} is the cumulative length of the projections of the circles of impact on the downslope side and L_{plot} is the length of the downslope side. The frequency (*F*) of events is then calculated as:

$$F = \frac{I_{total}}{a_{mean} \times CIP} \qquad (4)$$

where I_{total} represents the total number of documented rockfall impacts and a_{mean} the mean age of trees in the cell. Finally, the recurrence interval (*Ri*) is recalculated as the inverse of the frequency (*F*). CIP in this study was calculated for 10×10 m plots on the rockfall slope and a mean rock diameter of 40 cm (Favillier et al., 2017). The calculation routine was applied in ArcGIS Pro 2.3.3 (2019).

4 RESULTS
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The oldest tree-ring records from *F. sylvatica* date back to 1781, and the youngest tree-ring records dates back to 1965. The mean DBH of trees is 33.1 cm. The spatial distribution of disturbed trees, their DBH and the division of the studied slope can be observed in Figure 4. The prevailing social status of the trees was co-dominant (35 % of trees), followed by dominant (31 % of trees), supressed (27 % of trees) and pre-dominant (7 %). The sampled trees were healthy and did not show any signs of other disturbances. Due to rockfall impacts, two trees were decapitated and two had missing branches.

General statistics for the study plot are summarized in Table 1. Altogether, 374 rockfall scars were counted on the stem surface of the *F. sylvatica* trees. The mean number of impacts per trees was 7, with the lowest number of scars being 1 and the highest 17.

The distribution of impacted trees shows higher rockfall frequency in the middle part of the studied slope and lower frequency on the lateral sides. The number of rockfall impacts varies from 10–17 per tree in the middle part of the slope (Figure 5) and 1–10 per tree on the lateral side. The number of scars per individual tree can vary significantly within the same sector, which is a consequence of the small-scale variability of rockfall processes (propagation of individual rocks, not massive mass movement).

Comparing scar age, 67 % of the scars were classified as “old scars”, 33 % as “medium-age scars” and only 2 % as “fresh”. The majority of impacts were (looking in the downslope direction) in the middle part of the tree stem (42 %), 30 % of the scars were located on the left part of the stem and 28 % on the right part of the stem. Five trees had no scars on the left part, four

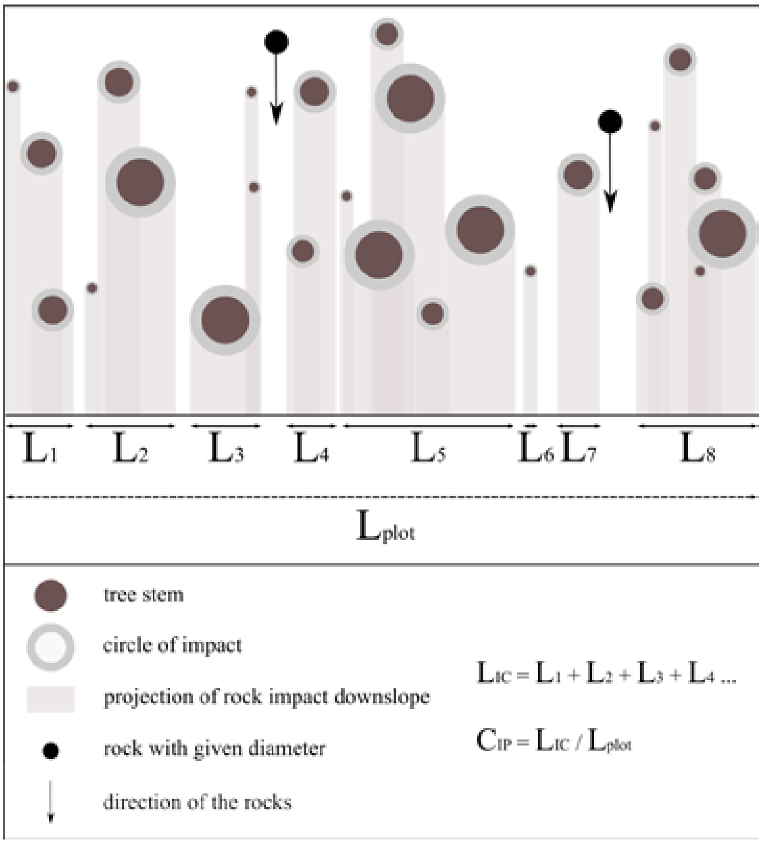

Fig. 3: The concept of the conditional impact probability (CIP) (the concept and figures after Moya et al., 2010b, Favillier et al., 2017): 1) CIP is calculated based on geometric analysis of the spatial distribution of all trees. 2) The impact circle is calculated using: cell boundary (in this study 10×10 m), tree stem (represented by DBH) and circle of impact (which represents DBH and average rock diameter together). 3) Projection of the impact circles on the downslope boundary of the cell analysis (area that is covered on the slope). L_1, L_2, L_3 and L_4 (...) are the width of the projection of the impact circle on the downslope boundary of the cell analysis. L_{plot} is the width of the analysis cell.

Slika 3: Koncept pogojne verjetnosti vpliva skale na drevo (CIP) (koncept in slika povzeta po: Moya in sod., 2010b, Favillier in sod., 2017): 1) CIP se izračuna na podlagi geometrijske analize prostorske razporeditve vseh dreves. 2) Vplivno območje drevesa v obliki kroga upošteva: rastrsko celico obdelave (v tej študiji 10×10 m), deblo drevesa (prek prsnega premera) in krog vpliva okrog drevesa (prek prsnega premera in povprečnih dimenzij skal). 3) Krog vpliva na posamezno drevo se projicira na spodnjo mejo rastrske celice obdelave (območje, ki ga s tem pokriva na pobočju). L_1, L_2, L_3, in L_4 (...) so širine projekcije kroga vpliva na spodnjo mejo rastrske celice. L_{plot} je širina posamezne analizirane celice.

Table 1: Overview of statistics on the number of impacts and their impact heights on trees, tree age and DBH, and calculated rockfall recurrence interval

Preglednica 1: Pregled statistike števila poškodb in njihovih višin na deblih dreves, starosti dreves in prsnega premera ter izračunanih povratnih dob pojavljanja skalnih podorov

measured data of 52 trees *izmerjeni podatki 52 dreves*	*Fagus sylvatica* mean / *povprečje*	 max / *max*	 min / *min*
DBH (cm) *prsni premer (cm)*	33.1	64.0	11.5
number of impacts per tree *število poškodb na drevo*	7	17	1
mean tree age on the plot *povprečna starost dreves na ploskvi*	166.5	237	53
mean recurrence interval in years *povprečna povratna doba v letih*	31.8	162.0	8.5
average height of the scars on tree stems (cm) *povprečna višina poškodb na deblu dreves (cm)*	66	350	0
average height of the scars on the left side of the tree stem (cm)* *povprečna višina poškodb na levi strani dreves (cm)**	60	250	0
average height of the scars on the right side of the tree stem (in cm)* *povprečna višina poškodb na desni strani dreves (cm)**	56	180	0

* looking in the downslope direction / *gledano v smeri pobočja navzdol*

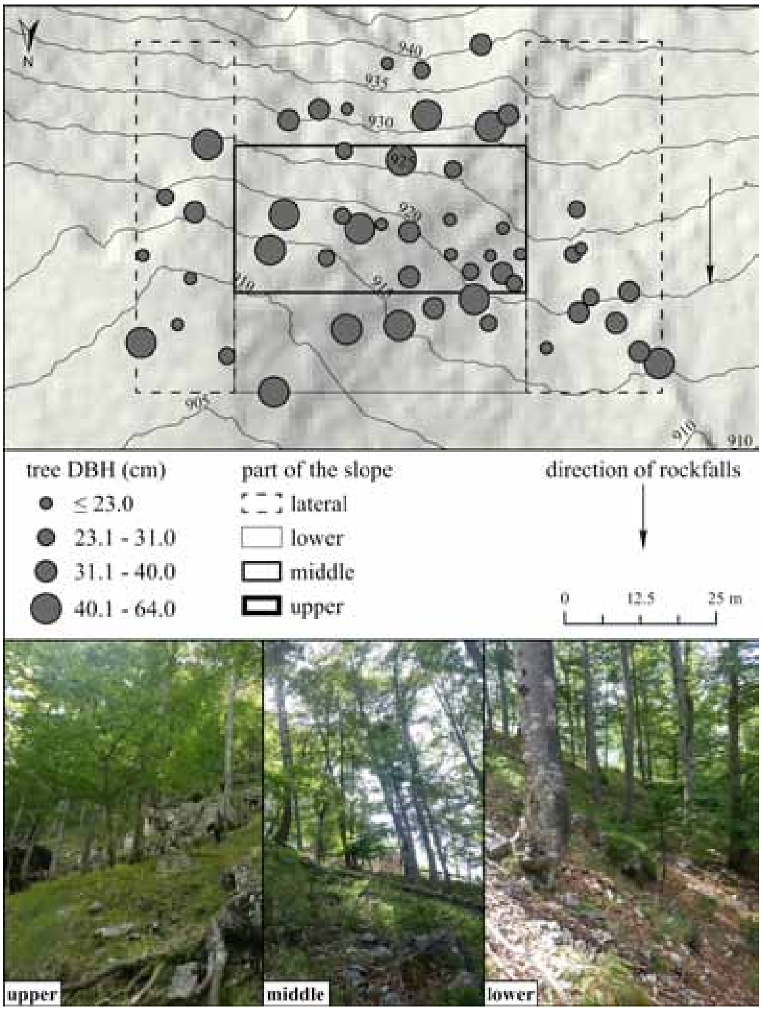

Fig. 4: Division of the studied slope into upper, middle, lower and lateral parts, along with a presentation of the spatial distribution of the disturbed trees and their DBH

Slika 4: Delitev preučevanega pobočja na zgornji, srednji, spodnji in stranski del pobočja ter prikaz prostorske porazdelitve poškodovanih dreves glede na prsni premer dreves

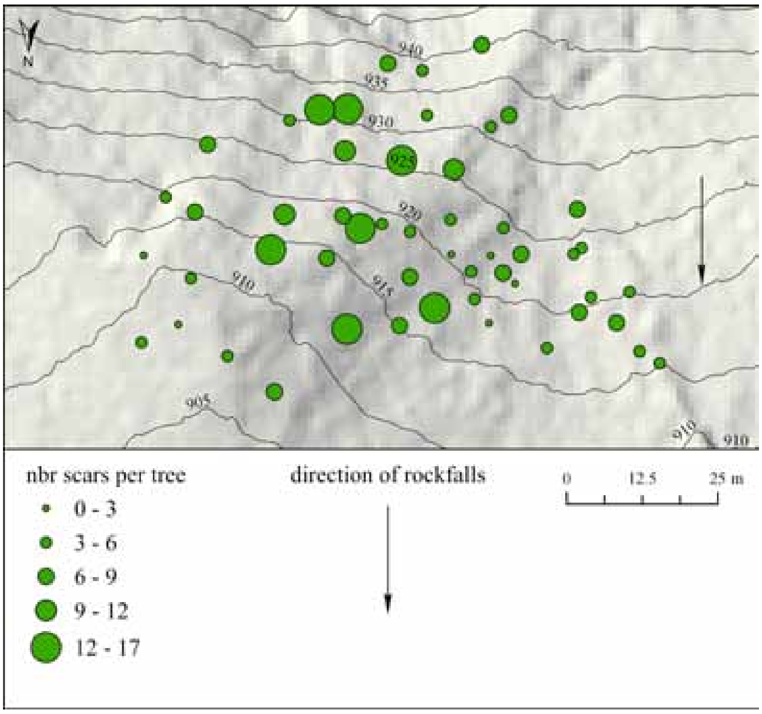

Fig. 5: The number of impacts of rockfalls per individual tree

Slika 5: Število poškodb zaradi skalnih podorov na posameznih drevesih

trees had no scars in the middle part and two had no scars in the right part of the stem. In the case of one tree, scars were only present in the middle part of the tree stem. On average, scars were located at a height of 66 cm; the highest scars were located in the middle part of the tree stem (78 cm), while the lowest were on the right side of the stem (56 cm). Although, the location and number of scars varies between the stems, it is not possible to distinguish any particular trajectory paths of past rockfall events based on this information.

The spatial pattern of rockfall impacts on trees shows that rockfall activity is more frequent in the middle part of the studied slope. Using a standard dendrogeomorphic approach, an average recurrence interval (Ri) of 31.8 years was calculated (Figure 6A). The lowest Ri was 8.5 years and the highest 162 years. The largest part of the area (53.63 % of the studied slope) falls in the 16–30 year recurrence period (22 trees), followed by 31–50 years (19 trees), which covers 32.10 % of the studied slope, and 51–75 years (6 trees), which represents 8.50 % of the slope (Table 2).

If a tree has approximately 10 injuries, the recurrence interval is 20 years. For 7 injuries (average number of injuries in this study) it is 30 years, and for 3 injuries it is 40 years (Figure 7). Higher Ri can be distinguished in the upper part of the slope and in the central part of the studied plot where the likelihood of a rock hitting a tree is higher.

There is a weak positive correlation between tree DBH and the number of injuries per tree, meaning that trees that have a larger DBH record more injuries (Figure 8A). A similarly weak trend can also be observed between tree age and recurrence interval (Figure 8D), where the recurrence interval is longer for older trees. However, there is no correlation between tree DBH and Ri or between tree age and the number of injuries

Table 2: Number of trees and the percentage of area of each recurrence period interval with and without CIP.

Preglednica 2: Preglednica 2: Število dreves in delež proučevanega območja posameznega intervala povratne dobe brez in z CIP.

	Ri without CIP *Ri brez CIP*		Ri with CIP *Ri z CIP*	
recurrence period (years) *povratna doba (leta)*	% of the studied slope *% proučevanega pobočja*	number of trees in this area *št. dreves v tem območju*	% of the studied slope *% proučevanega pobočja*	number of trees in this area *št. dreves v tem območju*
0 – 15	5.73	4	7.29	6
16 – 30	53.63	22	53.90	23
31 – 50	32.10	19	31.01	18
51 – 75	8.50	6	7.77	4
76 – 100	0.02	0	0.0	0
101 – 115	0.02	1	0.02	1

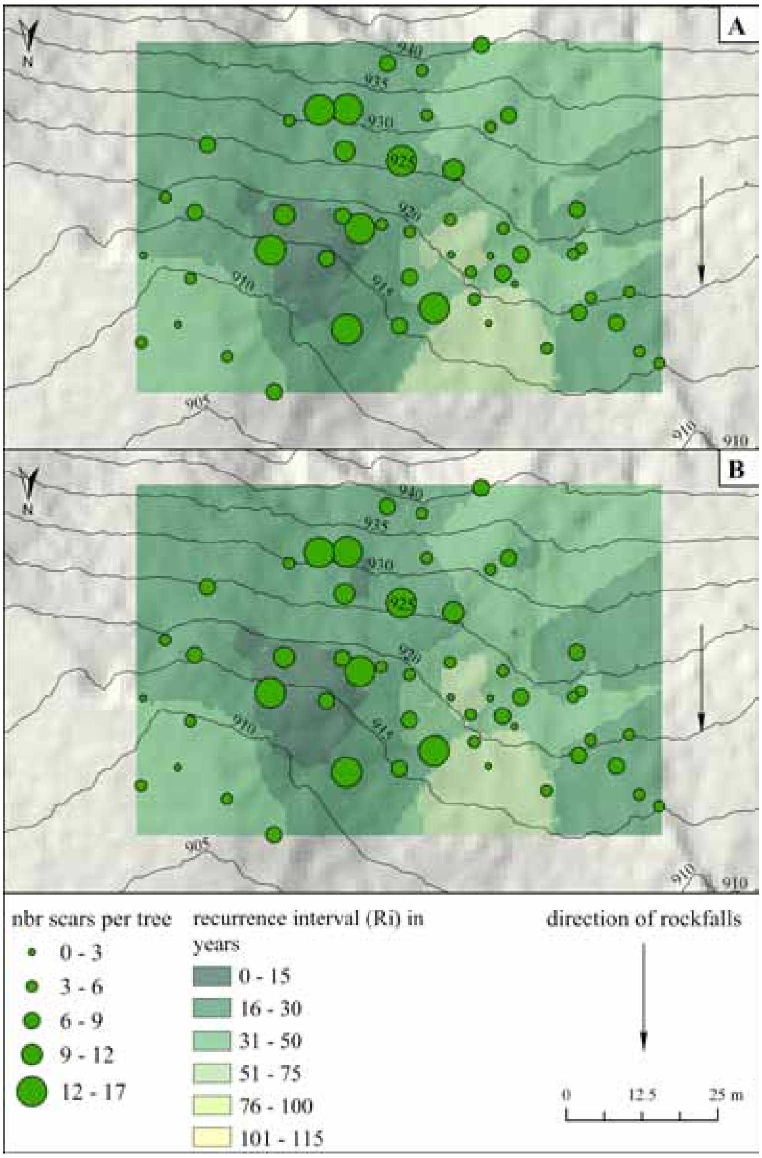

Fig. 6: Recurrence interval (Ri) of rockfall impacts A) without taking into account the conditional impact probability (CIP) approach and B) with conditional impact probability (CIP). Ri is shown in time intervals of 15 years.

Slika 6: Povratna doba (Ri) pojavljanja skalnih podorov A) brez upoštevanja pogojne verjetnosti vpliva skale na drevo (CIP), in B) Ri korigiran s pogojno verjetnostjo vpliva skale na drevo (CIP). Ri je na karti prikazan v časovnih intervalih 15 let.

(Figure 8B, 8C). The trees with a longer recurrence interval have an impact on the trend line, which is mainly because the number of those trees is lower, and there is a larger gap between the maximum recurrence interval and the following recurrence intervals. These trees represent rockfalls of smaller dimension and spatial extent.

The recurrence interval was adjusted according to the CIP (Figure 9), namely it can be observed that values vary from 5 to 46 %, with a mean of 17.3 % (missing rockfall events). CIP is mainly impacted by the spatial distribution of trees; the highest probability is recorded in the lower, central part of the slope where trees are close together and not positioned in straight lines and parallel to each other, which means that there is no “shadow effect” among trees. The mean DBH of trees in the sector with the highest average CIP is 32.3 cm. The lowest CIP is in the upper part of the slope. After adjusting the recurrence interval by applying the CIP, the Ri drops by 1.2 years on average (min 0.3 and max 6.2 years) (Figure 9), which means that the average Ri changes to 30.6 years. The changes in the recurrence interval are the largest in the lowest part of the slope where the density of trees is highest (Figure 6B). When taking into account the CIP approach, the largest part of the studied slope is also in the 16–30 year recurrence period (53.90 % of the slope, 23 trees), followed by 31–50 years (31.01 % of the studied slope, 18 trees) and 51–75 years (7.77 % of the slope, 4 trees) (Table 2).

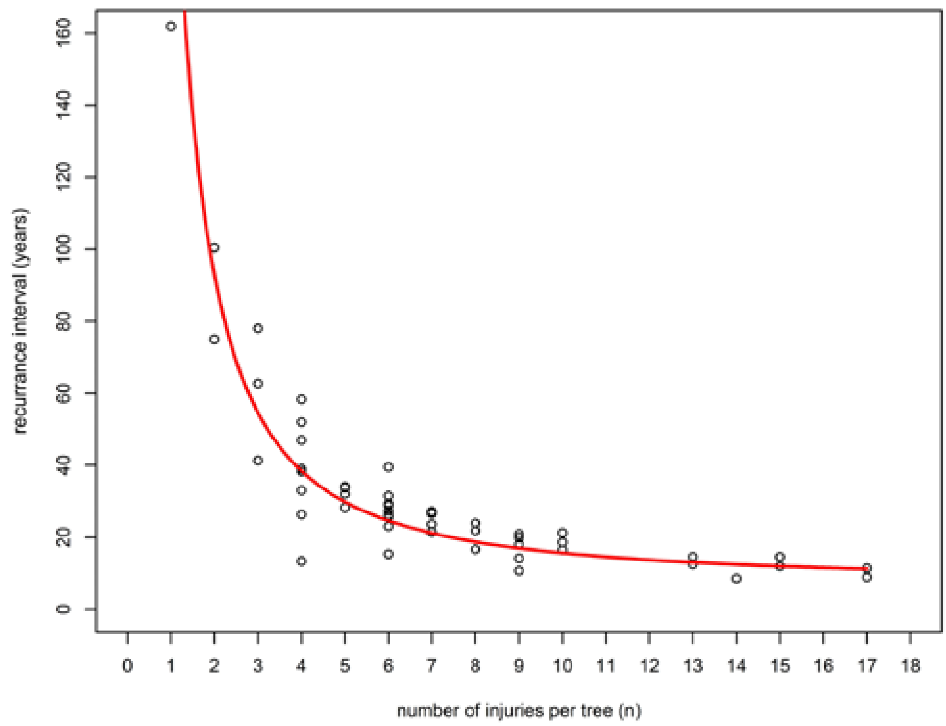

Fig. 7: Correlation between the number of injuries per tree and recurrence interval (Ri)

Slika 7: Povezava med številom poškodb na drevo in povratno dobo (Ri)

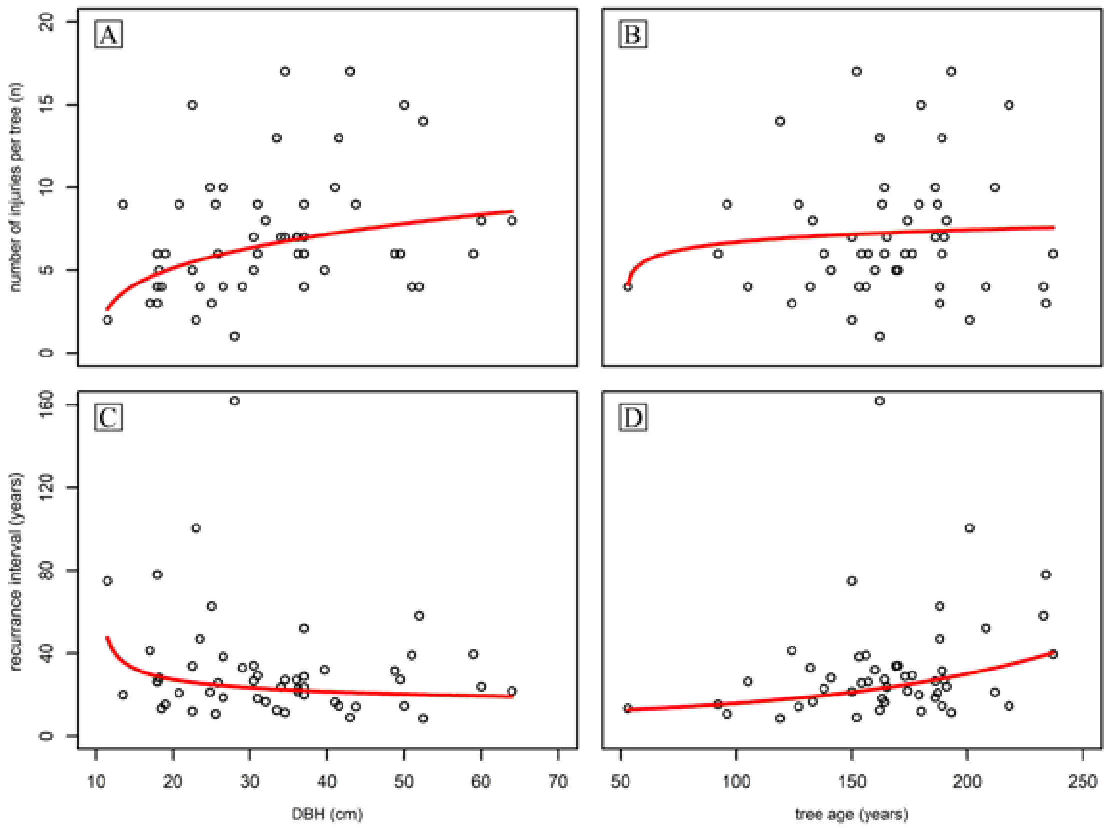

Fig. 8: Correlation between A) tree DBH and the number of injuries per tree, B) tree age and the number of injuries per tree, C) tree DBH and recurrence and D) tree age and the number of injuries per tree

Slika 8: Soodvisnost med A) prsnim premerom drevesa (DBH) in številom poškodb na drevo, B) starostjo drevesa in številom poškodb na drevo, C) prsnim premerom drevesa (DBH) in povratno dobo, ter D) starostjo drevesa in povratno dobo

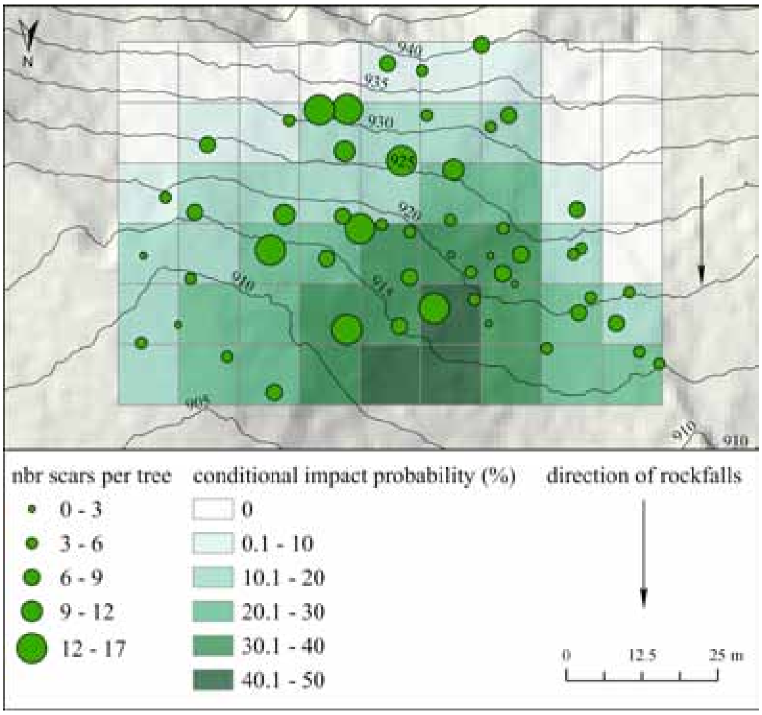

Fig. 9: Conditional impact probability (CIP) calculated for individual 10×10 m plots

Slika 9: Pogojna verjetnost vpliva skale na drevo (CIP), izračunana za posamezne celice velikosti 10×10 m

5 DISCUSSION AND CONCLUSION

5 RAZPRAVA IN ZAKLJUČKI

In this study we present a methodology for reconstructing the spatial pattern of rockfall activity based on the approach presented by Trappmann and Stoffel (2013). The reconstruction was based on counting the scars on 52 disturbed *Fagus sylvatica* trees. The results of this study show that the highest number of rockfall impacts occurred in the middle part of the slope, while lower rockfall activity was observed on both lateral sides of the slope. Recurrence intervals were the shortest in the middle part of the slope, which can be explained by the topography of the potential release area. On the western part of the slope, the area is cut by a large past rockfall event (rock deposits) and a vertical rock wall – the past rockfall slope acts as a barrier for falling rocks since they are stopped on the rocky slope and thus do not reach the forest. On the eastern part of the slope, a small gap with no trees can be observed, meaning that rocks falling there do not face as many obstacles as in the central part of the slope. Therefore, they can travel longer distances and their impact is not recorded on the trees. Trees in the central part of the slope are more densely distributed and have larger DBH and can therefore record more rockfall events. The recurrence intervals did not show significant correlation with tree DBH or tree age, and thus these parameters did not have a biasing effect on the derived rockfall recurrence interval. The majority of scars were classified as older, indicating a lower amount of recent rockfall activity. New scars were smaller, indicating that rocks with smaller dimensions frequently fall down the slope. Based on the location of scars on the stem, it was not possible to distinguish the prevailing direction or change in direction of falling rocks.

Using the CIP approach, we adjusted the Ri in order to estimate the number of missing rockfall events which did not leave any scars on the tree stems. The CIP showed the highest rates of potentially missed events in the lowest, western part of the slope since the highest density of trees lies in this trajectory line. After applying the conditional impact probability, the recurrence interval on average drops by 1.2 years. Since the CIP is applied based on raster blocks (in this case 10×10 m), the final result strongly depends on block diameter – this can potentially lead to over or under estimation of conditional impact probabilities (Favillier et al., 2017).

Although this approach is simpler than the traditional dendrogeomorphic approach, it has proven to achieve comparable results (e.g. Trappmann and Stoffel, 2013, 2015; Favillier et al., 2017). The scar-counting approach can provide insight into past rockfall activity and a more accurate number of past events compared to observing growth anomalies in tree-ring records, where past events can be missed due to the limited number of increment cores that can feasibly be extracted during a field campaign. The downside of the scar-counting approach, however, is the overestimation of rockfall activity since one rock can potentially cause several scars on one tree by bouncing or fragmenting on impact with the tree (Trappmann et al., 2013; Favillier et al., 2017). Moreover, compared to classical dendrogeomorphic techniques, scar counting does not result in precise chronologies of past rockfall events. In our study the size of the scars was not taken into account, but the size of the scar can have an important impact on the healing process and thus on the extent to which rockfall activity is masked. Namely, smaller scars can heal faster (Schweingruber, 1996), meaning that some rockfall events can be missed, and the actual recurrence interval would then be shorter. In the case of small wounds, detection of hidden scars is only possible through multiple sets of cores at different trunk heights (Stoffel et al., 2005; Stoffel and Perret, 2006). However, Stoffel (2005) was able to identify 75 % of visible scars on the tree stem of a 112-year-old Fagus sylvatica, which indicates that almost all scars would remain visible on the stem surface if they were not blurred by later impacts on already affected areas (Trappmann and Stoffel, 2013).

In conclusion, the method is effective for quick spatial reconstruction of rockfall patterns, especially on larger scales where there are temporal and spatial limitations. The method is especially suitable for calibration and validation of rockfall models, particularly when setting up parameters of modelling and evaluating model results (Corona et al., 2013, 2017).

6 SUMMARY

6 POVZETEK

V prispevku smo predstavili metodologijo prostorske rekonstrukcije aktivnosti skalnih podorov, ki sta jo uvedla Trappmann in Stoffel (2013). Metoda je še posebej primerna za preučevanje poškodb na listopadne drevesne vrste, kot je bukev, ki ima gladko in tanko skorjo, ki se zlahka poškoduje zaradi udarca skal. Poleg tega poškodb, nastalih zaradi vpliva skalnih podorov, ne zakrijejo tako hitro kot iglavci, ki poškodbe običajno prerastejo v nekaj letih. Posledično nam analiza poškodb na tovrstnih drevesih omogoča dolgoročno prostorsko-frekvenčno rekonstrukcijo pojavljanja skalnih podorov. V naši študiji smo za rekonstrukcijo aktivnosti uporabili pristop štetja vidnih poškodb na deblu 52 dreves navadne bukve (*Fagus sylvatica* L.), in sicer na območju pojavljanja skalnih podorov v dolini Trente (Zadnja Trenta). Frekvenco pojavljanja skalnih podorov smo določili na podlagi števila poškodb na posamezno drevo in izračunom povratne dobe pojavljanja dogodkov, hkrati pa smo s pomočjo prostorske interpolacije analizirali pojavljanje skalnih podorov na območju preučevanega območja. Povratne dobe smo korigirali z vrednostmi pogojne verjetnosti vpliva skale na drevo (CIP), ki pri izračunu povratnih dob upošteva tudi verjetnost, da so skale zgrešile drevesa in tako niso pustile sledi aktivnosti. Poškodbe na deblih smo kategorizirali v tri skupine glede na starost poškodbe (stara, srednje stara, sveža). Za izračun povratnih dob smo poleg analize vidnih poškodb na deblu dreves določili še starost dreves prek izvrtkov.

Povprečno število poškodb na posamezno drevo je bilo 7 in maksimalno 17. Rezultati analize poškodb kažejo, da je največje število poškodb zaradi skalnih podorov moč zaznati v osrednjem delu pobočja, medtem ko je bila manjša aktivnost zaznana na obeh lateralnih straneh obravnavanega območja. Večino poškodb na deblih (63 %) smo klasificirali kot zelo stare poškodbe, kar nakazuje na zmanjšano aktivnost proženja skalnih podorov v zadnjih letih. Poškodbe, ki so bile kategorizirane kot nove (2 % dreves), so manjših dimenzij, na kar nakazujejo tudi manjše velikosti skal in opazovane odložene skalne gmote. Povprečna višina poškodb na drevesu je bila 66 cm; najvišji vpliv je bil v osrednjem delu debla, na višini 78 cm. Kljub temu, da so lokacije in število poškodb različni na posameznih deblih, na podlagi teh podatkov nismo mogli rekonstruirati trajektorijev poti skalnih gmot.

Povprečna povratna doba pojavljanja skalnih gmot je znašala 31,8 leta; najkrajša je bila 8,5 leta in najdaljša 162 let. Najkrajša povratna doba je bila zaznana v osrednjem, zgornjem delu pobočja, kar je mogoče razložiti z izoblikovanostjo površja potencialnega območja proženja skalnih podorov. V zahodnem delu pobočja, kjer se območje stika z večjim skalnim podorom, je zaradi odložitve večjega števila skalnih gmot nastala ovira, ki omejuje prehod novih skalnih gmot v gozd, saj se bodo odložile že na samem območju ostalih skal. V vzhodnem lateralnem delu pobočja je v gozdu vrzel (območje brez dreves), kar pomeni, da skale na območju premeščanja nimajo ovir. Tako je njihova dolžina odlaganja daljša, prav tako pa dogodki niso zabeleženi. Osrednji del pobočja ima največje število dreves in hkrati zajema največjo površino obravnavanega območja, kar nakazuje na največji vpliv skalnih podorov ravno v tem delu.

Z uporabo metodologije CIP smo prilagodili rezultate dolžin povratnih dob z upoštevanjem dogodkov skalnih podorov, ki potencialno niso pustili nobenih poškodb na drevesih. Največje število manjkajočih dogodkov je bilo zabeleženo v zahodnem, spodnjem delu pobočja, kjer je tudi največja gostota dreves. V povprečju se na celotnem preučevanem območju povratna doba zniža za 1,2 leta. Ker je bila metodologija uporabljena na podlagi 10×10 metrskih rastrskih celic, je končni rezultat odvisen tudi od velikosti rastrske celice – kar lahko pripelje do precenjevanja ali podcenjevanja vrednosti CIP.

Uporabljena metodologija je v primerjavi s tradicionalnim dendrogeomorfološkim pristopom (preučevanje anomalij v drevesnih branikah) poenostavljena, vendar z njeno uporabo lahko dosežemo primerljive rezultate, hkrati pa nam omogoča vpogled v preteklo aktivnost skalnih podorov. Tako lahko z njeno uporabo rekonstruiramo celo več preteklih dogodkov, kot bi jih le ob študiji drevesnih branik, kjer se lahko posamezni dogodki prikrijejo. Pristop štetja poškodb na deblu dreves vseeno lahko privede do precenjevanja pretekle aktivnosti, zato jo je treba uporabljati kritično. Do precenjevanja pride predvsem zaradi trkov skale z več drevesi in fragmentacije skale ob trku ob drevo, ko se le-ta lahko razdrobi na več delov ter tako povzroči več poškodb hkrati. Dodatna slabost metode je, da preteklih dogodkov ne moremo rekonstruirati v času. Kljub temu je predstavljena metodologija učinkovita za hitre prostorske rekonstrukcije aktivnosti skalnih podorov na večjih območjih. Metoda je še posebej primerna za kalibracijo in validacijo prostorskih modelov za modeliranje skalnih podorov, saj lahko podatke uporabimo za določitev vhodnih parametrov in oceno natančnosti rezultatov modeliranja.

7 ACKNOWLEDGEMENTS
7 ZAHVALA

The study was financially supported by the Interreg Alpine Space projects ROCKtheALPS (ASP 462) and GreenRisk4ALPs (ASP 635). For the permission of the field work activities, the authors would like to express their gratitude to the agrarian community of the village of Trenta. The first author would like to thank the Pahernik Foundation for providing funding for tuition for the doctoral study of Biosciences - Managing forest ecosystems. The authors would also like to thank the anonymous reviewers for improving the manuscript.

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