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LETTER

The effects of forest cover and disturbance on torrential hazards: large-scale evidence from the Eastern Alps

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Abstract

Global human population growth, limited space for settlements and a booming tourism industry have led to a strong increase of human infrastructure in mountain regions. As this infrastructure is highly exposed to natural hazards, a main role of mountain forests is to regulate the environment and reduce hazard probability. However, canopy disturbances are increasing in many parts of the world, potentially threatening the protection function of forests. Yet, large-scale quantitative evidence on the influence of forest cover and disturbance on natural hazards remains scarce to date. Here we quantified the effects of forest cover and disturbance on the probability and frequency of torrential hazards for 10 885 watersheds in the Eastern Alps. Torrential hazard occurrences were derived from a comprehensive database documenting 3768 individual debris flow and flood events between 1986 and 2018. Forest disturbances were mapped from Landsat satellite time series analysis. We found evidence that forests reduce the probability of natural hazards, with a 25 percentage point increase in forest cover decreasing the probability of torrential hazards by 8.7%$\pm$ 1.2%. Canopy disturbances generally increased the probability of torrential hazard events, with the regular occurrence of large disturbance events being the most detrimental disturbance regime for natural hazards. Disturbances had a bigger effect on debris flows than on flood events, and press disturbances were more detrimental than pulse disturbances. We here present the first large scale quantification of forest cover and disturbance effects on torrential hazards. Our findings highlight that forests constitute important green infrastructure in mountain landscapes, efficiently reducing the probability of natural hazards, but that increasing forest disturbances can weaken the protective function of forests.

Introduction

Global human population growth in combination with an increasing demand for recreational activities have led to a strong increase of human infrastructure in some mountain regions around the globe (e.g. the European Alps, the Northern Front Range of the Rocky Mountains) (Casteller *et al* 2018). These settlements and infrastructure are highly exposed to natural hazards such as rockfall, avalanches, and torrential hazards (i.e. debris flow and flooding). As a result, global losses from these natural hazards increased by almost 70% within the last 30 years (MunichRe 2019). In the Eastern Alps, torrential hazards caused damages of 877 million € (~1 billion US dollars) between 1972 and 2004, and 49 people lost their lives as a result of such events (Oberndorfer *et al* 2007). This underlines the strong need to protect humans and their infrastructure from torrential hazards in mountain regions.

An important means to address the risk from natural hazards are technical measures, such as snow barriers, rockfall nets, dams, and retention areas. Austria,

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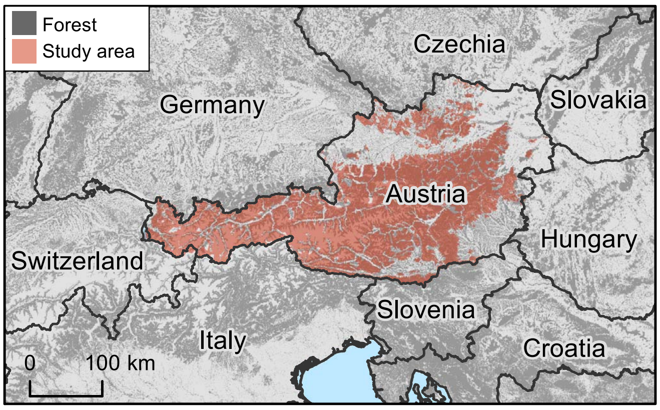

Figure 1. Map of the study area. The red areas mark the study area, whereas the grey parts indicate forest cover.

for example, currently directs more than 85% of the resources used to combat natural hazards into the construction and maintenance of such technical measures (BMNT 2018). However, it has long been established that forests are efficient in providing protection against natural hazards (Swanson *et al* 1998, Brang *et al* 2001). They contribute to slope stability in steep terrain as their rooting systems reinforces and stabilizes the soil (Amann *et al* 2009). Additionally, forests buffer surface runoff during peak precipitation events through canopy water interception and improved soil infiltration, and are thus able to reduce soil erosion in torrential watersheds (Sakals *et al* 2006).

In contrast to technical measures, forests are dynamic systems that change over time. This means that also the services they provide to society are not static but vary over time (Wohlgemuth *et al* 2017, Albrich *et al* 2018). Natural disturbances (i.e. large pulses of tree mortality from natural causes such as windthrow events, wildfires, or bark beetle outbreaks) are integral drivers of mountain forest dynamics (Kulakowski *et al* 2017). Disturbances open up the forest canopy and decrease leaf area, substantially reducing the protective function of forests (Thom and Seidl 2016). Specifically, disturbances reduce the protective effects of forests by increasing precipitation through-fall and surface water runoff, as well as by decreasing the live root density in the soil. Also forest management interventions such as timber harvesting open up the forest canopy. However, as they are applied deliberately to regenerate forests, they are frequently seen as an important means to maintain the long-term protective function of forests against natural hazards (Brang *et al* 2006, Streit *et al* 2009). Recent quantitative studies indicated, however, that unmanaged forests provide a higher level of protection against natural hazards than managed forests (Irauschek *et al* 2017, Mina *et al* 2017, Seidl *et al* 2019). It thus remains unclear how forest disturbances—both natural and human—affect the occurrence probability and frequency of torrential hazards.

The currently available evidence on the effects of forest cover and disturbance on torrential hazard risk largely stems from local case studies (Brardinoni *et al* 2003, Imaizumi *et al* 2008, Nyman *et al* 2015), and large-scale investigations on the efficiency of forest protection against natural hazards are largely missing (but see Bradshaw *et al* 2007, Yin *et al* 2018). This knowledge gap is problematic, as a push towards a bio-based economy increases the pressure on forest ecosystems, e.g. increasing harvest levels across Europe's forests (Levers *et al* 2014). Furthermore, natural disturbances are intensifying across Europe (Seidl *et al* 2014, Senf *et al* 2018) as a result of past land use and anthropogenic climate change. The ongoing large-scale changes in forest disturbances call for an assessment of their impacts on the protective effect of forests, in order to provide robust recommendations to forest managers and political makers.

A major limitation for large-scale research on the effects of forest disturbances on torrential hazards is the lack of consistent large-scale data sets on both disturbances and torrential hazard events. However, recent efforts to systematically catalogue torrential hazard events (Heiser *et al* 2019) and identify forest disturbances using remote sensing data (Senf *et al* 2017) offer new avenues for quantitative analyses. We here build upon these recent developments by quantifying the effects of forest cover and canopy disturbances on the probability of torrential hazards in the Eastern Alps, jointly analyzing 31 years of disturbance data and 3768 documented torrential hazard events for 10 885 watersheds. Specifically, we address three research questions:

I. Does forest cover reduce the probability and frequency of torrential hazard events?

II. How do forest disturbances influence the probability and frequency of torrential hazard events?

III. If forest disturbances influence the occurrence probability and frequency of torrential hazards, how does their effect differ with disturbance type?

Data and methods

Study area

We focused our analysis on the Eastern Alps in Austria (figure 1). The geology of the central parts of the mountain range is dominated by crystalline bedrock (i.e. granite and gneiss), whereas the northern and the southern front ranges are characterized by calcareous bedrock. Mean annual precipitation varies greatly with elevation and location, and ranges from 600 mm on the dry and warm eastern slopes of the Alps to >2500 mm in high elevation areas of the northern front range. Mean annual temperature ranges from 11 °C in low-lying areas in the east to below −5 °C in areas above the timber line in the center of the range (ZAMG 2019). Over the entire study area, the mean annual temperature between 1986 and 2018 was 7.3 °C, with an average annual precipitation of 1098 mm (ZAMG 2019). In total we analyzed 10 885 watersheds covering an area of 4.8 million hectares, and spanning an elevational gradient from 114 to 3725 m a.s.l. The mean watershed area is 437 ha (minimum of 4 ha and maximum of 19 843 ha) and the mean elevation is 996 m a.s.l.

The mean forest cover of the investigated watersheds is 63%. The natural vegetation composition changes along an elevational gradient. In elevations <600 m a.s.l. forests are dominated by broadleaved species (primarily European beech [*Fagus sylvatica* L.] and oak species [*Quercus ssp.*]). In mid elevations between 600 and 1200 m a.s.l. mixed broadleaved and coniferous forests (dominated by European beech, Norway spruce [*Picea abies* (L.) Karst.] and silver fir [*Abis alba* Mill.]) form the natural vegetation. Forests in elevations above 1200 m a.s.l. are naturally conifer-dominated (Norway spruce, European larch [*Larix decidua* Mill.], and Swiss stone pine [*Pinus cembra* L.]). The tree-line is generally situated between 1800 and 2200 m a.s.l. and is often characterized by a *krummholz* belt of mountain pine [*Pinus mugo* Turra]. Forest structure and species composition have been strongly modified by forest management as most parts of the study area have experienced intensive land use over the past 300 years (Bebi *et al* 2017).

Disturbance data

We created disturbance maps at a spatial grain of 30 m and at annual resolution for the period from 1986 to 2016 based on all available Collection 1 Level 1 surface reflectance images from the USGS Landsat archive. We employed state-of-the-art disturbance detection algorithms (Kennedy *et al* 2010, Cohen *et al* 2018) implemented in the Google Earth Engine cloud computing platform (Gorelick *et al* 2017, Kennedy *et al* 2018). The algorithm first builds annual best-observation composites from all available Landsat images. Subsequently, it segments each annual time series into linear segments of either stable, declining or increasing vegetation conditions based on the individual spectral bands and a series of spectral indices. This segmentation is used to identify forest canopy disturbances (see Kennedy *et al* 2010 for details) at the level of an individual pixel. A random forest model (Breiman 2001) is subsequently applied to classify each pixel in any given year into disturbed or stable conditions, filtering for the false positives frequently occurring with automatic disturbance detection algorithms (Cohen *et al* 2017). We calibrated and validated the random forest models using 1828 pixel-based reference data collected in a previous study (Senf *et al* 2018). Annual disturbance probabilities were aggregated into a map indicating the year of the first disturbance. The overall map accuracy was 90.5% (<0.1% SE) with balanced errors of omission (19.6%, SE 0.8%) and commission (19.3%, SE 0.8%).

Torrential hazard data

We define hazards according to IPCC (2012), describing physical events that have caused damages to human infrastructure or livelihood. Torrential hazards are hazards from ravines, creeks, rivers, and streams in small, steep headwater catchments. Information about torrential hazard events was extracted from the Austrian torrential event catalogue (Hübl *et al* 2008). This database contains torrential events that have caused damage to humans or human infrastructure in small steep headwater catchments. In addition, it provides shapefiles describing the watershed outlines and the torrential event locations. From 1986 to 2018, 3768 torrential hazard events were recorded in 2018 watersheds, whereof 2646 were flood events and 1122 were debris flow events. As reference condition for our analysis we selected all watersheds which did not experience any torrential events between 1980 and 2018 (i.e. 8867 watersheds). We here extended the time period in order to omit watersheds that experienced a torrential event just before 1986. Flood processes in steep headwater catchments are characterized by variable sediment transport rates with a volumetric concentration of solid particles in water of up to 20% (ONR-24800 2014). Coarser particles are transported as bedload, moving much slower than the water stream. In contrast, sediment concentrations of debris flow events can exceed 40% (ONR-24800 2014), and particles and water travel at the same velocity. While differing in their constitutive features both debris flow and flood events are triggered by heavy rainfall events and are capable to relocate and deposit large amounts of material from the slopes to the valley bottoms. This frequently results in damaged roads and destroyed houses.

Table 1. Predictors for modeling the probability of torrential hazards. For the values and range of all predictors see supplement SI 4.

Domain	Predictor	Definition	Expected effect on torrential hazard probability	Source
Geography	Area	Area of focal watershed in km^2	+	
	Elevation	Mean elevation of watershed in m a.s.l.	+	
	Infrastructure	Area share covered by urban infrastructure in focal watershed in %.	+	Pflugmacher *et al* 2019
	Ecoregion	The ecoregion in which the majority of the focal watershed is situated		Kilian *et al* 1994
Geomorphology	Melton ratio	$\frac{\text{Elevation}_{max} - \text{Elevation}_{min}}{\sqrt{\text{Area}}}$	+	Melton 1957
	Elevation ratio	$\frac{\text{Elevation}_{max} - \text{Elevation}_{mean}}{\text{Elevation}_{max} - \text{Elevation}_{min}}$	+	Wood and Snell 1960
	Elongation	$\frac{\text{Diameter of a circle with area of watershed}}{\sqrt{\text{length}_{max}\text{ of watershed}}}$	−	Schumm 1956
	Circularity	$\frac{\text{Area}}{\text{Area of a circle with circumference of watershed}}$	−	Miller 1953
Forest	Forest cover	Forest cover of watershed in %	−	Pflugmacher *et al* 2019
	Patch density	Number of forest patches per km^2 i.e. forest distribution in the watershed ranging from contiguous to patchy	+	Pflugmacher *et al* 2019
Disturbance	Extent	Forest canopy cover disturbed between 1986 and 2016 in %	+	
	Type	$\text{Gini}_{\text{coefficent}}(\overrightarrow{[\text{yearly disturbance extent }]})$	−	
	Extent x Type	Interaction between extent and type (see supplement SI 3)	+	

Geographical and geomorphological watershed attributes

We derived three geographical attributes for each watershed from remote sensing products in order to adjust for differences in extent, elevation and level of human infrastructure exposed to natural hazards (table 1, section *Geographical)*. We expected larger watersheds and watersheds with a high level of human infrastructure to have a higher probability of being affected by torrential hazards. The level of exposed human infrastructure was approximated as the relative proportion of urban areas within each watershed, based on a 2015 land cover map with a spatial resolution of 30 m, created from Landsat satellite data (Pflugmacher *et al* 2019). As precipitation increases with elevation in our study area and torrential hazards are frequently triggered by periods of heavy rainfall, we included elevation to account for differences in exposure between watersheds. Furthermore, to account for climatic and geological differences among watersheds we also controlled for the ecoregion (according to Kilian *et al* 1994) in our analyses (see supplement SI 1 available online at stacks.iop.org/ERL/14/114032/mmedia).

We described the geomorphological predisposition of a watershed to torrential hazards based on indicators which have been identified as influential in previous studies (table 1, section *Geomorphology)*. Heiser *et al* (2015) analyzed 11 fluvial geomorphometric parameters with regard to their influence on torrential processes. Based on their findings we selected the Melton ratio (Melton 1957) as well as the elevation relief ratio (Wood and Snell 1960) as geomorphological predictors of torrential processes. In addition, we also included circularity (Schumm 1956) and the elongation ratio (Miller 1953) in our analysis to account for the specific form of watersheds.

Forest- and disturbance-related watershed attributes

To evaluate the role of forests and canopy disturbances on the probability of torrential hazards we used four indicators, i.e. forest cover, forest patch density, disturbance extent and disturbance type (see table 1 section *Forest*). Forest cover was calculated as the relative proportion of forested area within a watershed in 2015 based on a 30 × 30 m land cover map (Pflugmacher *et al* 2019). As forest cover changes over time we also tested how land-use change influences our results (see supplement SI 2). Forest patch density was derived by dividing the number of distinct forest patches (using an eight-cell-neighborhood to identify patches) by the total watershed area. The indicator thus describes the distribution of the forest area within the watershed, ranging from contiguous forest cover to highly patchy forest cover.

Canopy disturbances occur as a result of timber logging (clearcutting as well as thinning) or natural forest disturbances (i.e. primarily windthrow and insect infestation) in our study area. Since previous studies showed that the attribution of satellite-based disturbance patches to different causes of canopy disturbance remains challenging (Hicke *et al* 2012, Kasischke *et al* 2013, Oeser *et al* 2017, Senf *et al* 2017), we here jointly analyzed canopy disturbances from both human and natural causes. Specifically, we calculated two indices describing the disturbance regime of a watershed based on the annual disturbance maps described above (Section *Disturbance data*), i.e. disturbance extent and disturbance type (see supplement SI 3). Disturbance extent describes the relative forest area of a watershed affected by canopy disturbances over the 31-year study period. Disturbance type describes the temporal distribution of disturbances, with *pulse disturbances* happening in a short period of time and *press disturbances* being distributed regularly over the study period (Bender *et al* 1984). To derive a continuous indicator between the two poles of pulse and press disturbance we calculated the Gini coefficient of the annual forest area affected by canopy disturbances. A Gini coefficient of one indicates a pulse disturbance regime signifying that the disturbance of a watershed occurred in one year. A Gini index of zero indicates a press disturbance regime signifying that equal areas were disturbed every year between 1986 and 2016. High Gini values mean maximum inequality in the annually disturbed area and low values mean minimum inequality in the annual area disturbed. In addition to the ecological relevance of distinguishing between pulse and press disturbances, disturbance type also serves as a proxy for the dominant disturbance agent in our study region. While human-induced canopy disturbances (i.e. clearcutting and thinning) are generally small but occur regularly (i.e. *press* disturbance), natural disturbances are potentially large but only happen rarely (i.e. *pulse* disturbance). We *a priori* checked for correlation between forest cover and disturbance extent/type. We found only a weak correlation of Pearson's $r = 0.18$ for disturbance extent and Pearson's $r = -0.11$ for disturbance type. For an overview of the range of variability within the data see supplement SI 4.

Statistical analysis

All analyses were conducted at the watershed scale. We developed separate models for the occurrence and frequency of debris flow and flooding. For modelling the occurrence, we assumed a Bernoulli distribution, where the occurrence probability p_i in watershed i is modeled by a linear combination of all predictor variables $\boldsymbol{X_i}$ (see table 1) using a logistic link function:

$$\begin{aligned} \text{Occurence}_i &\sim \text{Bernoulli}(p_i) \\ p_i &= \text{logit}^{-1}(\boldsymbol{\beta X}_i). \end{aligned} \tag{1}$$

In equation (1), the vector $\boldsymbol{\beta}$ contains the direction and strength of each predictors (see table 1) effect on the probability of occurrence.

To model the frequency of torrential hazard events we assumed a negative binomial distribution, predicting the count of events per watershed over the study period. The mean μ_i is modeled by a linear combination of all predictor variables $\boldsymbol{X_i}$ using a log link function to assure positive response values:

$$\begin{aligned} \text{Count}_i &\sim \text{Negativebinomial}(\mu_i, \phi) \\ \mu_i &= \log^{-1}(\boldsymbol{\beta X}_i). \end{aligned} \tag{2}$$

In equation (2) the parameter ϕ is a dispersion parameter accounting for over-dispersion and is estimated from the data.

We used Bayes' rule to calculate posterior distributions of all model parameters (i.e. the intercept and effect sizes contained in $\boldsymbol{\beta}$ as well as the dispersion parameter ϕ) from the model likelihoods and prior parameter distributions assigned to each parameter. After z-transforming the data, we used $N(0,\ 0.5)$ priors for $\boldsymbol{\beta}$ and an $\text{Exp}(1)$ prior for ϕ. Those priors can be seen as weakly informative, regularizing priors that prevent the model from overfitting the data. Joint posterior distributions were sampled using Monte-Carlo-Markow-Chain (MCMC) methods implemented in the Software Stan (Carpenter *et al* 2017) via the *rstanarm* package (Stan Development Team 2016). We used four chains à 4000 iterations, with the first 2000 iterations dropped as warm-up samples. We checked the convergence of the chains via the $\hat{\text{R}}$ statistic (Gelman *et al* 2014a). The $\hat{\text{R}}$ statistic compares the variability within and between chains and approaches one if all four chains converge to a similar solution. We further evaluated whether the model fitted the data properly by performing posterior-predictive checks (Gelman *et al* 2014a), that is drawing randomly from the model and comparing the draws to the observed data. If the model is well specified, there should be no substantial deviation between model draws and observed data (see supplement SI 5 and SI 6).

We fitted and compared different predictor combinations to test the importance of different predictor domains (see table 1). First, we fitted a null model containing only an intercept, assuming constant torrential hazard probabilities across all watersheds. Subsequently, we successively included predictors of the domains *geography*, *geomorphology*, *forest* and *disturbances*, resulting in a total of five models with increasing model complexity. We compared all five models by estimating the approximate leave-one-out expected log predictive density (LOO-ELPD; Vehtari *et al* 2017). The LOO-ELDP is a relative measure of model performance—similar to the Watanabe–Akaike information criterion—but preferable in most settings (Gelman *et al* 2014b). In essence, it estimates the predictive accuracy of the model when confronted with unknown data. Thus, a positive difference in ELPD between two competing models implies a better predictive performance of the second model. However, as the ELPD itself is uncertain, we assume a difference in ELPD to be only meaningful whenever it is two standard deviations larger than zero.

We finally summarized and compared the joint posterior distributions from the full models of both occurrence probability and frequency to gain insights into the direction and strength of each covariate. We further drew posterior predictive distributions for fixed values of disturbance extent and type (holding the watershed predictors constant), in order to further investigate the effects of different disturbance regimes on the occurrence probability and frequency of torrential hazard events.

The data that support the findings of this study are openly available at Sebald (2019):

https://doi.org/10.6084/m9.figshare.9758891.v1

Results

In line with our expectations, the *geographical* watershed characteristics were important for controlling for differences in watersheds across our study area (large difference in ELPD compared to the null model; table 2). Larger watersheds had a higher probability of one or more torrential events occurring. Watersheds in higher elevations had a higher occurrence probability and frequency of debris flow events, but a lower occurrence probability and frequency of flood events. The level of human infrastructure in a watershed had no influence on the occurrence probability and frequency of debris flows, but slightly decreased the occurrence probability and frequency of flood events (figure 2).

The *Geomorphological* characteristics were important for predicting occurrence probability and frequency of torrential events, substantially increasing predictive performance (table 2). Melton ratio, circularity and elevation ratio were positively related with occurrence probability and frequency of both hazards. Elongation was negatively correlated with flood events, but had a slightly positive correlation with debris flow events (figure 2).

Forest-related predictors also had an important effect on the occurrence and frequency of torrential events (table 2). Forest cover was the predictor with the strongest negative effect on occurrence probability and frequency of both hazards (figure 2). Compared to the average forest cover in the study area (i.e. 63%), an increase by one standard deviation in forest cover (i.e. to 88%) decreased torrential hazard probability by 8.7% ± 1.2%. A higher patch density, representing a distributed occurrence of forests over the watershed, also reduced the occurrence probability and frequency of torrential hazards. Compared to the average patch density (i.e. 6.5 forest patches per km^2) an increase by one standard deviation (i.e. to 12.5 forest patches per km^2) decreased debris flow probability by −8.2% ± 1.8% and flood probability by −5.7% ± 1.2% (figure 2).

Finally, also *disturbances* significantly influenced the occurrence and frequency of torrential events (table 2). Large disturbance extents increased the probability of debris flow events but had no significant effect on flood events. Furthermore, press type disturbances (i.e. disturbances occurring regularly across the study period) increased the probability of both debris flow and flood events (figure 2). For debris flow, the effect of disturbance extent was further modulated by disturbance type (figure 3). Here, the highest probability of occurrence was observed in watersheds with regular, large forest canopy disturbances. Given a press disturbance regime (Gini = 0), the annual probability of a debris flow event increased from 0.18% to 0.60% (+248%) when moving from 10% of the forest cover disturbed to 50% of the forest cover disturbed within the 31-year study period. In contrast, the probability did only moderately increase (+42%) for the same increase in disturbance extent under the average disturbance type, and no change was found for pulse disturbance regimes (Gini = 1, figure 3). A similar signal could be observed for hazard frequency, where the annual probability of two or more debris flow events increased from 0.03% to 0.15% (+466%) when moving from 10% of the forest cover disturbed to 50% of the forest cover disturbed in 31 years under a press disturbance regime (figure 4a). In contrast, there was only weak evidence for an interaction between disturbance extent and disturbance type for flood events (figure 2). Probability of occurrence and frequency of flood events were primarily influenced by disturbance type, increasing with press-type disturbances. For floods the annual probability of one event occurring within the 31-year study period increased from 0.22% to 0.40% (+83%), and the annual probability of two or more events from 0.03% to 0.21% (+ 530%) when moving from a pulse disturbance regime to a press disturbance regime (figure 4b). Including an interaction between disturbance type/extent and forest cover did not improve model performance compared to a model without this interaction (ELPD difference ± standard error for the debris flow model was 1.62 ± 2.64 and − 0.75 ± 1.37 for the flood model).

Discussion

We here for the first time quantified the effect of forest cover and disturbance on natural hazards across a large spatial domain, using a novel combination of remote sensing data and a national scale database on natural hazard events. Our findings highlight the importance of forests for mitigating torrential hazards for humans and their infrastructure. Across a wide social and ecological gradient, we found that the occurrence probability and frequency of torrential hazards was reduced with higher shares of forest cover in a watershed. This result is in line with the process-based understanding of mechanisms influencing the occurrence of torrential hazards,

Table 2. Improvement of predictive power with increasing model complexity. The table shows the model improvement compared to the previous level of model complexity (difference in ELPD ± one standard deviation; see section statistical analysis). Predictors were included in groups following the domains outlined in table 1. The first model, containing only predictors from the domain Geography (see table 1), is compared to a Null-model containing only an intercept (i.e. constant torrential hazard probabilities across all watersheds). An ELPD difference of more than two standard deviations is considered as a meaningful improvement (see Vehtari *et al* 2017 for details on interpreting the ELPD).

Response	Difference in ELPD (± SD)			
Predictor domains	**Geography**	**Geography + Geomorphology**	**Geography + Geomorphology + Forest**	**Geography + Geomorphology + Forest + Disturbances**
Debris flow				
Occurrence	+322 ± 25	+19 ± 7	+18 ± 6	+18 ± 6
Frequency	+361 ± 27	+28 ± 9	+15 ± 6	+15 ± 6
Flood				
Occurrence	+282 ± 27	+53 ± 11	+27 ± 8	+48 ± 10
Frequency	+351 ± 29	+59 ± 12	+18 ± 7	+ 53 ± 12

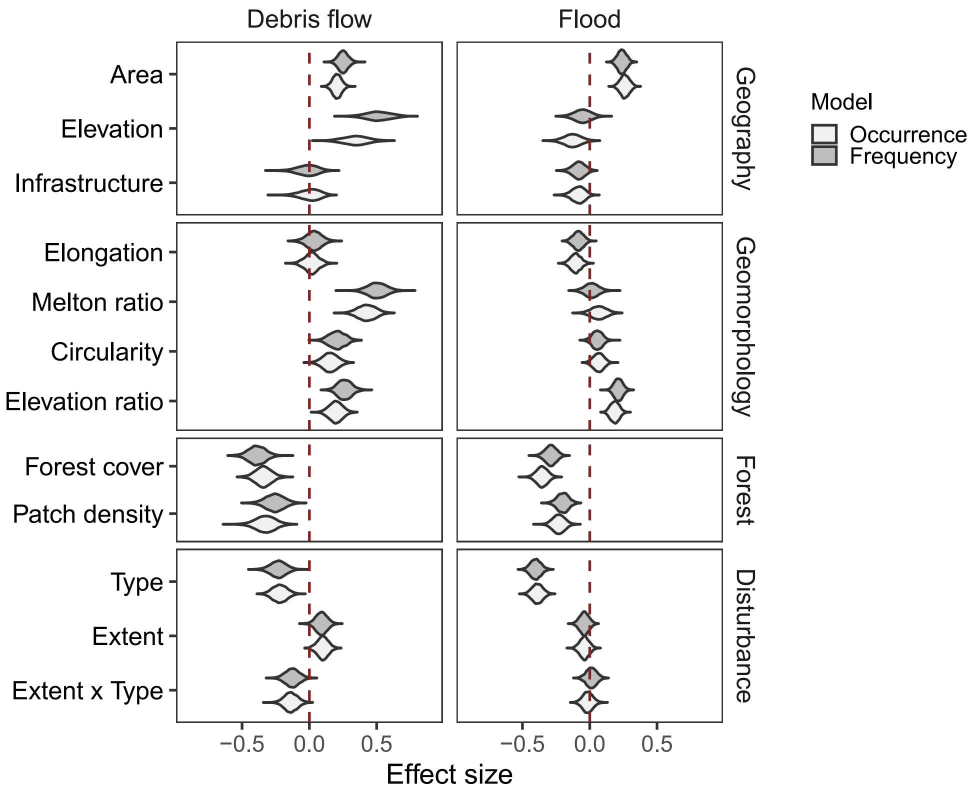

Figure 2. Posterior probability distribution of effect sizes for each predictor. The dashed line indicates no effect. Negative effects decrease the probability of occurrence/ frequency of torrential hazards, whereas positive effects increase the probability of occurrence/ frequency of torrential hazards. Effect sizes are given as standardized z-scores.

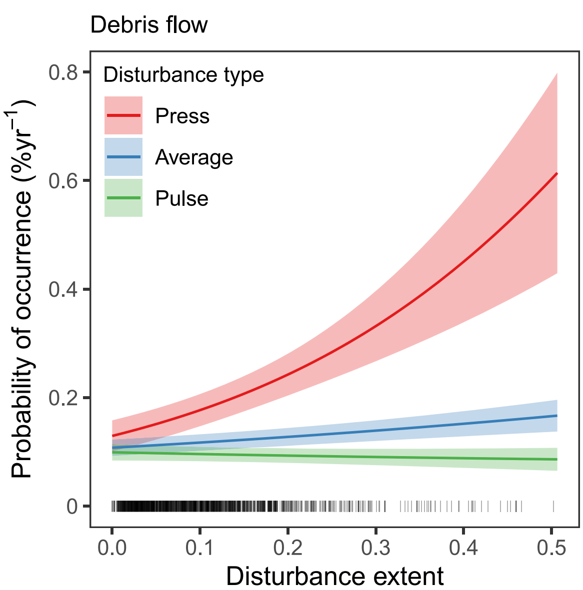

Figure 3. Predicted annual probability of occurrence for debris flow events based on the interaction between disturbance extent and disturbance type. Disturbance extent describes the proportion of forest area that was affected by disturbances between 1986 and 2016 (i.e. over a 31-year period). Press, average and pulse disturbance types here correspond to Gini coefficients of 0, 0.7, and 1, respectively (see table 1 for details). The data density is indicated by tick marks at the bottom of the panel. Note that the upper 1% of the data was excluded to facilitate visualization.

derived from local case studies (Imaizumi *et al* 2008, Moos *et al* 2016, Altieri *et al* 2018). Torrential events occur through hydrological transport of soil and debris from slopes, and their deposition in valley bottoms which are frequently settled by humans in the Alps. The amount of soil and debris that is deposited is determined by the availability of loose material on the slopes as well as the transportation rate of streams. Forests reduce the availability of material for transport as their root system stabilizes the soil and thus retains material on slopes (Sakals *et al* 2006). Furthermore, forests decrease stream transportation rates as their

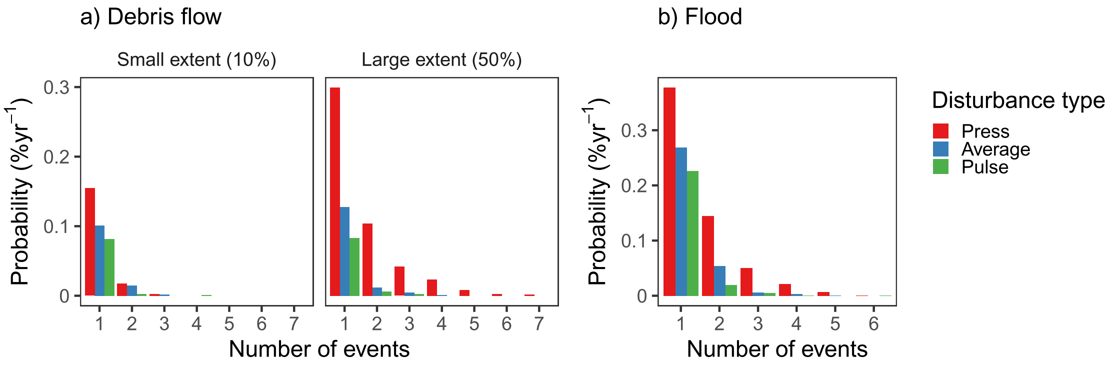

Figure 4. Predicted annual probability of occurrence of (a) debris flow and (b) flood events based on disturbance type and disturbance extent. Press, average and pulse disturbance types here correspond to Gini coefficients of 0, 0.7 and 1, respectively (see table 1 for details). Disturbance extent describes the relative forest area of a given watershed affected by canopy disturbances between 1986 and 2016. Please note that as disturbance extent did not significantly influence flood events (see figure 2), panel (b) solely displays the effect of disturbance type. Please also note the different scaling of y-axes between panels.

canopy intercepts precipitation. In addition, trees transpire water and thus free up pore space in the soil. In combination with improved soil water infiltration surface runoff is reduced (Noguchi *et al* 2001) and runoff peaks are dampened by forests, reducing sediment transportation rates.

While forests generally reduce the probability of natural hazards, this protective function can be weakened by increasing canopy disturbances. Our results provide clear evidence for a significant influence of forest canopy disturbances on the probability of torrential hazards, which is in line with findings from local studies (Roberts and Church 1986, Jakob 2000, Imaizumi *et al* 2008, Silins *et al* 2009, Buma and Johnson 2015). Disturbances reduce canopy cover and—with a time lag of a few years to decades—also rooting density in the soil, thus leading to elevated transportation rates and decreased soil stability. Disturbances also increase the amount of loose soil material available for transport in torrential events, e.g. via root plates of uprooted trees or erosion from logging activity. However, based on our analyses the extent of the detrimental effect of forest disturbances varies with disturbance regime. We found that regular canopy disturbances were more detrimental to the protection against torrential hazards than singular disturbance events. This can be explained by the fact that the risks from canopy disturbances are greatest in the years immediately after a disturbance event (Wohlgemuth *et al* 2017), and that both canopy disturbances and the heavy rainfall events triggering torrential hazards are rare. At low disturbance frequency the likelihood of a heavy rainfall event occurring immediately after a disturbance is also low. In contrast, if canopy disturbances happen regularly in a watershed, any heavy rainfall event will affect partly disturbed areas. Regular canopy disturbances thus increase the probability of torrential hazards, particularly if they affect a large portion of the watershed (figure 3, 4). This is of special relevance since there is growing evidence that both the occurrence of heavy precipitation events (IPCC 2012) and the frequency and extent of disturbances (Seidl *et al* 2017, Senf *et al* 2018) is increasing as a result of climate change.

Although our results are based on an exceptionally large empirical dataset (10 885 watersheds in which 3768 torrential events were recorded over a period of 31 years) and we combine these data with novel, comprehensive maps of canopy disturbance, it is important to consider the limitations of our materials and analyses. First, the disturbance maps created for this study are not able to capture sub-canopy disturbances (such as thinnings from below) or disturbances happening at the sub-pixel scale (i.e. <30 m horizontal grain). They thus give a conservative estimate of disturbance extent in our study area. Furthermore, an attribution of disturbances to different disturbance agents (e.g. insect infestation, wind breakage, logging etc) was not possible with our data and remains a major methodological challenge for remote sensing in Central Europe (Senf *et al* 2017). We circumvented this limitation by developing a novel indicator of disturbance type (see supplement SI 3) based on ecologically important disturbance characteristics (press-pulse disturbance, Bender *et al* 1984). Such a categorization has recently been found to hold high inferential potential e.g. in the assessment of disturbance effects on a wide range of ecosystem services (Cantarello *et al* 2017). Second, a limitation of the natural hazard events database used here is that only events which have caused actual damage to humans and/ or human infrastructure are recorded. Although even small damages are recorded (e.g. a minor amount of debris being deposited on a road by a creek), our data (i) likely underestimate the total amount of torrential events that occurred, and (ii) might be skewed towards watersheds with significant levels of human infrastructure. We controlled for the latter by including a proxy of human infrastructure in our analysis. However, watersheds with a high level of human infrastructure frequently also have a higher level of technical hazards mitigation measures, such as dams and overflow basins. As such measures reduce the damage caused by torrential hazards (Holub and Hübl 2008), they might introduce a bias in our analysis.

This effect could explain the slightly negative correlation of our infrastructure variable with occurrence probability and frequency of flood events (figure 2). Third, we note that factors not considered here might influence the probability and frequency of torrential hazards. Those include, e.g. the frequency of high intensity rainfall event, which was not considered explicitly in our analysis. Further, the probability and frequency of torrential hazard events might also be affected by differences in the hydrological system, and in particular by differences in technical measures of flood control (i.e. dams).

The large-scale evidence for a strong link between forest cover, canopy disturbance and torrential hazards provided here is of crucial importance for forest management. For instance, guidelines for the management of protective forests in the Alps propose frequent, small-scale logging interventions to increase structural diversity and continuously regenerate the forest (Motta and Haudemand 2000, Frehner *et al* 2005, Brang *et al* 2006). However, our results suggest that forest management in torrential watersheds should aim for as little interventions as possible to keep the probability of torrential hazards low. This insight is in line with recent simulation-based studies across the Alps, finding that non-intervention management is best able to provide regulating ecosystem services and protect against natural hazards (Irauschek *et al* 2017, Langner *et al* 2017, Mina *et al* 2017, Seidl *et al* 2019). A major concern of managers in this regard remains the thread of large-scale natural disturbances (Wohlgemuth *et al* 2017). However, the return intervals of such events are an order of magnitude lower than those of regular management interventions in the Eastern Alps (100–300 years and 10–30 years, respectively, Thom *et al* 2013). And while natural disturbances from wind and bark beetles can have strong detrimental effects on the local protection function against natural hazards (Badoux *et al* 2006, Brang *et al* 2006), our large-scale analysis revealed that their overall impact remains limited due to their low frequency. Natural disturbances could, however, become more influential in the future, as they are widely expected to increase in frequency and magnitude (Seidl *et al* 2017, 2014). In conclusion our study provides important empirical evidence for the efficiency of forests as green infrastructure protecting against torrential hazards and highlights the complex effects of canopy disturbances on forests and the services they provide to society.

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