PUBLIZIERBARER ENDBERICHT

A) Projektdaten

Kurztitel:	FIRIA
Langtitel:	Fire Risk and Vulnerability of Austrian Forests under the Impact of Climate Change
Programm inkl. Jahr:	ACRP 3rd Call
Dauer:	01.05.2011 bis 30.04.2014
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Projekt- und KooperationspartnerIn (inkl. Bundesland):	Institut für Waldbau, Universität für Bodenkultur (BOKU), Wien alpS Centre for Climate Change Adaptation Technologies, Tirol
Schlagwörter:	Waldbrand, Klimawandel, Naturgefahren
Projektgesamtkosten:	299.594 €
Fördersumme:	299.594 €
Klimafonds-Nr:	B068712
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B) Projektübersicht

1 Kurzfassung

Mit der Zunahme von warmen und trockenen Witterungsphasen in den Sommermonaten ist eine Zunahme der Waldbrandhäufigkeit in den Alpen zu erwarten. An steilen Hängen können Waldbrände die Schutzfunktion der Wälder herabsetzen, was die Wahrscheinlichkeit für sekundäre Naturgefahren erhöht. Es ist jedoch noch unzureichend bekannt, welche Waldgesellschaften besonders betroffen sind, wie lange die Regeneration nach schweren Feuern dauert, welche Naturgefahrenprozesse drohen, wie sich der rezente Klimawandel auswirken wird und welche waldbaulichen Maßnahmen ergriffen werden sollten. Tirol als unser Schwerpunktgebiet ist einer der "hot spots" in Österreich und wird vermutlich stark vom Klimawandel betroffen werden; außerdem sind hier mehrere Hänge bekannt, deren Vegetation nach Waldbränden stark degradiert wurde.

Das **erste Ziel** war es, die Steuerfaktoren für die räumliche Verbreitung von Waldbränden zu ermitteln; dazu war zunächst eine Erweiterung und Zusammenführung der existierenden Feuerstatistiken in einer einheitlichen Datenbank vonnöten. Das **zweite Ziel** war die Modellierung der Feuergefahr in Tirol unter heutigen Klimabedingungen. Zur Entwicklung einer digitalen Karte der Feuergefährdung in Tirol mussten die vorhandenen Punktdaten mit Hilfe von digitalen Geländemodellen, Karten der Waldgesellschaften und weiteren Geodaten regionalisiert werden, um mögliche "hot spots" von sekundären Naturgefahren nach Waldbränden zu lokalisieren. Das **dritte Ziel** war die Erstellung einer Karte der zukünftigen Feuergefahr unter Berücksichtigung von sich evtl. verschiebenden Häufigkeit und Intensität von feuergefährlichen Wettersituationen unter Klimawandelbedingungen. Das **vierte Ziel** war die Analyse, welche möglichen Naturgefahren (insb. Lawinen und Steinschlag) durch Waldbrände verstärkt werden könnten und welche Siedlungen und Infrastrukturen potenziell gefährdet sind.

Folgende Ergebnisse wurden erzielt:

– Eine online verfügbare **FireGIS Datenbank** wurde eingerichtet und ist zugänglich für die Öffentlichkeit, Feuerwehren und Wissenschaftler (http://fire.boku.ac.at). Nutzer können einfache Abfragen starten und sich die exakte Position vergangener Waldbrände (ca. letzte 25 Jahre) in interaktiven Karten anzeigen lassen. Außerdem können neue Brandereignisse gemeldet werden. Die Datenbank zeigt, dass die Waldbrände aufgrund der Akkumulation trockener Biomasse hauptsächlich im Frühjahr liegen; ein sekundäres Maximum im Sommer ist jedoch erkennbar und wird möglicherweise in der Zukunft an Bedeutung gewinnen.
– Karten der Topographie, Waldbedeckung und anthropogenen Infrastruktur wurden für die räumliche **Modellierung der Feueranfälligkeit** vorbereitet. Verschiedene klimatische, topographische, sozioökonomische und Vegetationsparameter wurden bezüglich ihrer Auswirkung auf die Waldbrandverteilung getestet, zwölf flächendeckende Parameter wurden schließlich für die Modellläufe ausgewählt. Es wurden zwei selbstlernende Modellalgorithmen verwendet: MaxEnt und randomForests. Beide Modellergebnisse stimmen darin überein, dass

das Lokalklima (Anzahl der Überschreitungstage eines bestimmten Feuerwetter-Index-Schwellenwerts) und Bevölkerung (Einwohnerdichte und Nachbarschaft zu Gebäuden) die wichtigsten Steuerparameter darstellen. Beide Faktoren führen zu einer Konzentration der Feuergefahr entlang der trocken-warmen und dicht besiedelten Tallagen. Allerdings lieferten die Programme unterschiedliche Einschätzungen der Bedeutung von z.B. Waldgesellschaft und Topographie.

– Multitemporale **Vegetationskartierungen** von abgebrannten Hängen verschiedenen Alters zeigten eine extrem unterschiedliche Regenerationsgeschwindigkeit, mit einer ungefähren mittleren Zunahme der Waldbedeckung von 10% der Fläche pro Jahrzehnt. Die Steuerparameter für die ausgeprägten räumlichen Unterschiede wurden mit Hilfe einer logistischen Regressionsanalyse untersucht; die Ergebnisse zeigen, dass eine Kombination von steiler Hangneigung, größerer Höhenlage, Südexposition und Kalkstein-/Dolomituntergrund sich besonders ungünstig auf die Regeneration auswirken.
– Regionale Klimawandelszenarien (RCMs) wurden für die Berechnung zukünftiger **Feuerwetter-Indizes** (FWIs) adaptiert. Die Szenarien zeigen einen Temperaturanstieg in der Zukunft, während die räumlichen Niederschlagsmuster relativ ähnlich bleiben. Aktuell sind die inneralpinen Trockentäler (z.B. Oberinntal, Iseltal in Osttirol) am stärksten betroffen; jedoch wird die Anzahl von Tagen mit hoher Feuergefährdung in Zukunft auch z.B. in Gebieten im Nordosten von Tirol ansteigen, die momentan noch nicht ausgesprochen feuergefährdet sind.
– Durch Verschneidung der Karten der Feueranfälligkeit mit der Verteilung der Schutzwälder wurden "hot spots" möglicher **sekundärer Naturgefahren** ermittelt. Für diese potenziell gefährdeten Gebiete wurden regionale und lokale Prozessmodelle für Steinschlag und Lawinen gerechnet. Die Ergebnisse zeigen, dass zahlreiche Gebäude im Falle von feuerbedingter Entwaldung gefährdet wären. Der durch Feuerschäden zusätzlich entstehende Schaden im Falle eines 150-jährigen Lawinenereignisses wurde auf über 100 M€ geschätzt, wohingegen der "worst case"-Schaden durch Steinschlag bei 50-100 M€ liegt. Beide Werte stellen nur eine erste Abschätzung mit erheblichen Fehlerspannen dar.

2 Executive Summary

Due to climate warming and higher probability of hot and dry spells in summer, a further increasing frequency and higher severity of wildfires is expected for the Alps. In steep alpine terrain, wildfires may affect the protective role of forests leading to enhanced probability of natural hazards. However, there are gaps of knowledge concerning the affected forest communities, the time taken for recovery after severe burns, the possible impact on post-fire geomorphic processes, the impact of climate change on the fire regime and possible adaptive silvicultural measures. We chose Tyrol as our study area because it is one of the hot spots in Austria and will probably be strongly affected by climate change, and where a number of slopes characterized by long-lasting wildfire-driven deforestation were identified.

The **first aim** of the project was to identify the driving factors of wildfires in Austria and their interdependence on various factors. The first step to achieve this aim was to improve and extend the existing forest fire database for all of Tyrol. The **second aim** was to model fire hazard for Tyrol

under current and future climatic conditions locating hot spots according to different climate scenarios. Developing a digital map of fire hazard in Tyrol required the regionalization of the point datasets using digital terrain models, forest community maps and further spatial data, to locate "hot spots" of post-fire natural hazards. The **third aim** was to produce a map of future fire danger, considering the changing frequency and intensity of fire-prone weather situations under climate change conditions. The **fourth aim** was to analyze, which natural hazards (focusing on rock fall and avalanches) might be enhanced by wildfires, and which infrastructures could potentially be at risk.

The following results were achieved:

- An online **FireGis Database** was established as a tool for the public audience, firefighter brigades and scientists. It is accessible via internet address: http://fire.boku.ac.at. Users can produce simple queries and find the exact position of past forest fires (mainly from the last 25 years) on an interactive map. Also users can report new fires to the workgroup. Spring and summer fires make up for a major part of forest fires in Austria because of the accumulation of dry fuels during winter. However, a secondary maximum in summer is already emerging and will become more important in the future.
- Topographic, infrastructure and forest maps were analyzed and prepared for model development of **fire susceptibility**. We tested different climatic, topographic, socioeconomic and vegetation parameters concerning their influence on fire distribution; twelve layers were finally selected for the model runs. The modelling of fire hazard under current climate conditions was carried out using two different machine learning methods, MaxEnt and randomForests. The models agreed on the main parameters responsible for spatial fire distribution which are climate (i.e. number of days surpassing a certain fire weather index threshold) and population (i.e. neighbourhood to buildings). Both lead to a concentration of forest fire susceptibility along the major valleys. However, the programs disagreed on the importance of vegetation and topography.
- Multitemporal **vegetation mappings** of recently burned slopes revealed that the speed of recovery is highly variable, with a mean regeneration rate of roughly 10% woodland vegetation in every 10 years. The governing parameters of regeneration were investigated using logistic regression analysis; it was found that sites with a combination of steep slope angle, relatively high elevation, sotherly orientation and limestone/dolostone bedrock are particularly prone to degradation.
- Regional scenarios of climate change were adapted for calculating **future fire weather indices** (FWI). The climate scenarios show an increase in temperature for the future while precipitation patterns remain similar. Currently, inner alpine dry valleys as the Upper Inn Valley or the Isel Valley in Eastern Tyrol are affected most; however, the number of days with high fire danger is going to increase in areas at mid and high elevation and also in areas of north-eastern Tyrol which are not particularly prone to fire danger today.
- Hot spots of fire danger were derived by combining fire hazard maps with the layer of protective forests. For these **hazard-prone areas**, regional and local scale process models for rockfall and avalanches were run under different forest fire impact scenarios. The results show

that numerous buildings are potentially affected in case of wildfire-driven deforestation; additional potential damage in case of a 150-yr avalanche event surpasses 100 M€ while the worst-case damage by rockfall is 50-100 M€. Both values are first approximations which are subject to considerable uncertainties.

3 Hintergrund und Zielsetzung

Austrian forests do not fulfil the characteristics of fire prone ecosystems, nor have they seriously been fire-impacted so far. However, two summer seasons (2003 and 2006) have most recently proved quite well how widespread and rapidly forest fires may happen and that they become an important issue if adequate weather conditions are given. Due to climate warming and higher probability of hot and dry spells in summer, a further increasing frequency and higher severity of wildfires is expected for the Alps. In steep alpine terrain, wildfires may affect the protective role of forests leading to enhanced probability of natural hazards. However, there are gaps of knowledge concerning the affected forest communities, the time taken for recovery after severe burns, the possible impact on catastrophic geomorphic processes, the impact of climate change on the fire regime and possible adaptive silvicultural measures. We chose Tyrol as our study area because it is one of the hot spots in Austria and will probably be strongly affected by climate change.

The first, basic objective was to collect and compile forest fire data for Tyrol. This included:

- Collecting data on occurrence, location and size, ignition date and time, duration and cause of forest fires by browsing fire statistics, literature, internet and newspaper information;
- Compiling supplementary information for each forest fire (slope, aspect, forest type, positional relation to settlements and infrastructure);
- Joining all data into a central FireGIS database which is accessible to all project participants, to stakeholders and to the public.

The next step was the modelling of fire susceptibility, including topographical (aspect, inclination etc.), ecological (forest type etc.) and socioeconomic parameters (e.g. distance to roads, railroads and villages, tourism, land-use). This included:

- Determining the main driving parameter using multiple-parameter statistics and self-learning algorithms;
- Creating a fire hazard map of present-day condition from the results.

The next objective was to investigate into climate – forest fire relationships and the consequences of ongoing climate change:

- Reconstructing fire weather conditions before historical fires from long-term climate records with focus on temperature and precipitation;
- Testing the applicability of several fire weather indices based on statistical measures using percentile analysis and logistic regression analysis;
- Adapting regional climate scenarios and extracting information on future fire weather indices;

- Localizing areas and periods of increased fire risk and creating a fire hazard map of future (climate change) conditions.

Secondary hazards following forest fires are dependent upon the degree of damage to the vegetation and the time of recovery; both are influenced by fire intensity. The aims here are:

- Collecting information on fuel load focussing on *Picea abies L., Pinus sylvestris* and *Larix decidua,* recording basic stand data including topographical parameters; building and evaluating fuel load models/classification;
- Mapping present-day site conditions of forest fire sites from orthophotos and terrain mapping; comparing the present-day conditions with historical conditions;
- Proposing schematic, typical succession models by compiling succession patterns at sites of different age; assessing the main influential factors on vegetation recovery by multi-parameter GIS analysis;
- Implementing information on fire vulnerability of different forest communities into the Tyrolean "Waldtypisierung".

The main concern regarding forest fires in Austria is the danger of secondary hazards like rockfalls, avalanches and debris flows. The objective was to locate possible "hot spots" of hazards after wildfire-driven deforestation, which includes:

- Process modelling on regional scale to get an overview of endangered areas; subsequent process modelling on local scale to specify the hazards;
- Vulnerability analysis concerning spatial planning aspects, infrastructures and lifelines;
- Producing vulnerability and risk maps as decision support and awareness building instrument;
- Providing recommendations for actions of appropriate risk management.

4 Projektinhalt und Ergebnis(se)

a) Activities and methods

Data collection for the study area was based on two already existing databases. Part one was delivered by BOKU and originated from the AFFRI project (Austrian Forest Fire Research Initative – H. Vacik), part two from the Tyrolean Limestone Alps came from the Alpine Wildfires project under supervision of O. Sass. These two sources had to be checked and compiled manually and included a total number of around 850 forest fires. By searching through additional sources (archives, chroniclers, commemorative books, personal meetings with local persons), further 550 fires were added to the database. The total number of located forest fires is about 1,400 since the 16th century. All data before the 20th century is incomplete and partial; however, it can be assumed that all forest fires reaching a significant size and impact on the forest have been recorded completely. For the examination period 1993-2011 which can be assumed to be reasonably complete, we could locate a total number of 482 wildfires. Those 482 fires were located as exactly as possible by checking the available photographs against aerial pictures, studying the local place names and topography and by consulting involved firemen or reporters. The geographic coordinate was stored including a buffer value in meters which describes the accuracy of the assumed ignition point. The mean accuracy (buffer) of the ignition points of all wildfires is 630 meters with a median value of 400 meters.

Extensive work had to be carried out to collect and compile all necessary **background data** and integrate it in the working space of a GIS and in a congruent projection system. The map data was delivered by various sources sources (TIRIS Tyrol, BFW Austria, Statistik Austria, partly supplemented by Open Street Map). Completion and falsification of all input data, deleting double line elements, merging roads and hiking trails and transforming the projection into one system turned out to be a time-consuming procedure. All vector data was transformed into raster files at a resolution of 5 x 5 meters to preserve the structure of line elements. These huge data files were used as an input to calculate a Euclidian distance raster and a density raster file for each map. One homogeneous forest layer was created out of five different maps (e.g. some forest maps covering only North Tyrol, others only Eastern Tyrol), and to split this layer into 100 x 100 meter polygons resulting into a total number of 694,704 forest cells. After these steps it was possible to calculate zonal statistics for every single forest-polygon. Finally, a set of parameters was created for every single cell and all those parameters were tested in a statistical approach to receive a set of primary parameters driving the forest fire frequency. For independent control of our modelling results we used two multivariate data mining techniques (MaxEnt and randomForests) in parallel.

Parameters which did not contribute to our model within the preceding test-runs were eliminated for the final modeling approach. One example was the density of power lines, another one was the forest stock (m^3/ha) which did not show any response to the fire ignition points.Twelve parameters were finally selected for the modeling process (Table 1).

Table 1: Parameters selected for the modelling process

Parameter group	Parameter	Abbreviation
Climate	1. Fire Weather indices (number of fire risk days)	fwi
Socioeconomic	2. Population density at r = 3 km	pers_h3000
Socioeconomic	3. Building density at r = 0.3 km	geb_300_NEU
Infrastructure	4. Railroad density	eisen_dichte
Infrastructure	5. Paved streets density	auto_dichte
Infrastructure	6. Forest roads and hiking trails density	frwa_di_me
Infrastructure	7. Aerial passenger lines density	auf_dichte
Vegetation	8. Forest type	wald_schiechtl_neu
Vegetation / Infrastructure	9. Forest protective management type	waldkat_maj
Topographic	10. Altitude	dem
Topographic	11. Slope	slope_median
Topographic	12. Aspect	aspect_maj

Using a non-parametrical statistical method we were able to select the best suited **fire weather index (FWI)** for the prediction of forest fire danger in Tyrol based on meteorological data. It is necessary to use different indices for summer and winter season and to differentiate areas with different ecological characterizations. For each eco-region in Tyrol a representative weather station was selected and the data were used for a period from 1960 – 2008 for the calculation of 19 different fire weather indices. The index which had the highest fire prediction performance was considered as the best working index for that eco-region. The same analysis was carried out separately for both seasons. The results show that for the summer season, the Canadian fire weather index and its sub-indices are well suited to predict fire danger, while in winter the M68dwd gives the best results. Based on the FWIs, five danger classes (1: low danger to 5: extreme danger) were defined using the observational INCA data set and using certain percentiles as thresholds.

To predict the **future fire danger** levels based on climate trends, three climate scenarios from the regional climate-models (RCMs) ALADIN, RegCM3 and REMO were bias-corrected and localized to a finer resolution. Bias-correction for each RCM was performed using a quantile mapping technique based on the E-OBS data set. The localization was done by superimposing local climate patterns obtained from the 1 km x 1 km resolution INCA data set to the RCM. Various model parameters, including temperature, precipitation, and relative humidity on a daily basis for the period 1951 – 2100 on a 1 km x 1 km grid for Tyrol were generated.

We carried out mapping of **vegetation** on slopes of varying age after fire from ortho images and personal inspection. Twenty-nine slopes (fire dates 1800 – 1970) were mapped in the first stage; for six of them, the development over time was investigated using sets of historical aerial photos from different years to derive timelines of tree regeneration. Parts of this work were carried out before the start of the FIRIA project; however, in FIRIA the results were collected, homogenized and put together. In the second stage (entirely in FIRIA), seven further younger slopes from 1990 – 2011 were mapped, all of them in a multitemporal approach with approx. four points in time for each, including the pre-fire situation. As intermediate fire ages (c. 1950 – 1990) were underrepresented in the dataset, we included two additional slopes from Upper Austria (Hagler, 1950+2003; Gimbach, 1961+2006).

The orthophoto mapping included forest stands, young stands, shrubland, grass of different coverage and bare rock/debris. For the later data analysis we focused on the percentage of woodland vegetation as a function of elapsed time after fire. In order to clarify the influential factors contributing to the observed regeneration patterns, we performed a GIS-based, multinomial logistic regression. The aim of the multivariate approach is to explain the distribution of the different types of land cover by a combination of independent site variables. As the independent variables are partly metric (e.g. elevation) and partly categorial (e.g. lithology), logistic regression turned out to be a suitable method. This approach belongs to the group of Generalized Linear Models (GLM).

After collecting **fuel data** from 57 sample plots all located in the vicinity of previous fire sites we were able to develop fuel models per sample plot. Due to the inhomogeneity of the fuel data it was not possible to identify groups of fuel models among the sample plots. The hypothesis was that similar fire behavior can be used to classify forest stands into classes of expected fire hazard; these models could then be used as additional input for a classification of fire danger in Tyrol. Selected case studies were simulated using known fire data and fuel models, results indicated the rate of mortality and hence the loss of protective functions.

Hazard assessment was carried out in a two-step procedure starting with regional models and later focusing on field investigations and data collection for local models. Regional hazard models for the identified hot spots delivered an unmanageable range of affected facilities. Hence, only a selection of infrastructures with the highest probability class from the regional model were taken into further account. Buildings were given a priority over all other facilities; single objects were dismissed. From this preselection the final investigation areas were derived. In total, 17 areas for avalanches and 9 areas for rockfalls were chosen for the local hazard assessment. The rockfall model Rockyfor3D version 5.1 and the avalanche model RAMMS version 1.5 were used.

For **rock fall modelling**, the input parameters for Rockyfor3D were collected in the field. For each spot, different scenarios were modelled regarding release volume settings and deforestation scenarios. For the release volumes the most abundant and the maximum blocksizes found in the catchment area were sampled, serving as the standard for most frequent and extrem events respectively. For **avalanche modelling**, avalanche release areas were determined for each hazard spots. Full deforestation of the 'high fire risk' areas was assumed. A three day snow fall period of an annuality of 150 years was matched to the respective regions to assess the highest possible event magnitude. For vulnerability and risk assessment for the two process types avalanche and rockfall, we considered the impact on buildings hosting public services, and the potential monetary losses of buildings associated with extreme events. The intensity of each process was classified differentiating low, medium and high impact according to thresholds of exerted force of impact or snow pressure, respectively. Punctional information on public services was pooled into six categories. The degree of actual damage and the associated monetary loss depends on the building's resistance and the magnitude of the process. Because of the lack of accurate data on the buildings' damage sensitivity, guidance values after Heinimann (1999) were utilised. The overlap with the modeled process intensity leads to the estimation of expected loss by applying an adequate damage function.

b) Results

A WebGIS based MySQL database was initiated in summer 2012 and is now under operational use. The **publicly accessible WebGIS application** allows all interested users to select forest fires through an interactive map and to generate individual statistics and graphs. The results can be selected using filters (e.g. districts, fire cause or size). Also, the specific background data (e.g. report of the fire brigade) can, if available, be accessed by clicking on the event in the map. Secondly, all users of the platform can report new wildfire events through a survey tool. The localization can be done with the help of a topographic map in the WebGIS application, additional information like fire cause, duration and burned area may be added and photos/videos of the event can be uploaded. The reports are reviewed by an administrator before they are added to the internal database. Moreover, the new forest fire portal brings together information on the current forest fire danger in Austria and Europe and gives an easy access to the forest fire blog, maintained by the Institute of Silviculture.

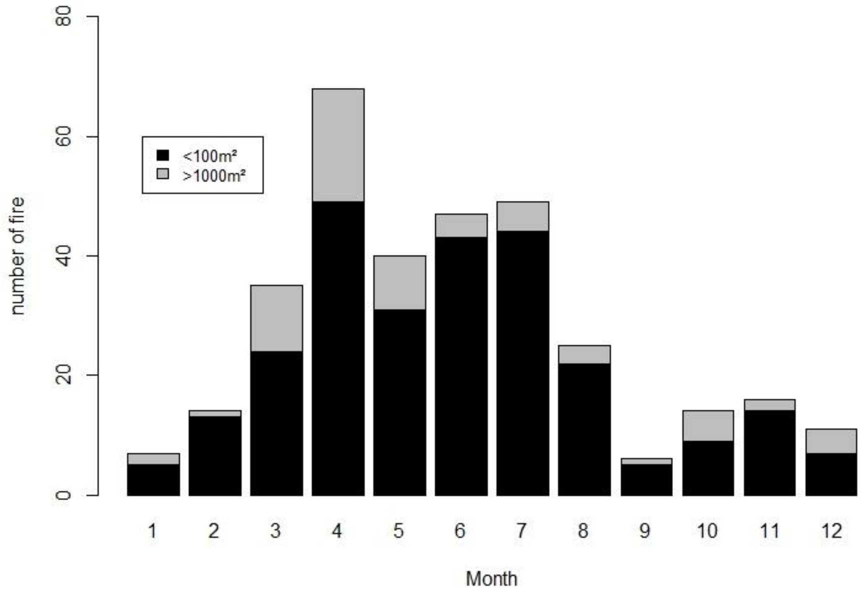

Figure 1: Temporal distribution of forest fires in the study area Tyrol between 1993-2012

The majority of documented fires had a size of more or less one hectare and was ignited due to anthropogenic reasons (74%). 20% of the forest fires in Tyrol ignited by lightning. Spring and summer are the main fire seasons (see Fig. 1). Coniferous forests are mainly affected by fires with the majority in Norway spruce (*Picea abies*) forests (39%), followed by Pine (*Pinus sp.*) forests with 26%. The major portion is ignited at south facing slopes (52%).

Both programs – MaxEnt and Random forests – found that certain parameters are of high importance for explaining **spatial fire distribution** while other factors are less relevant. The most important factors are climate (i.e. mean duration of critical fire weather conditions) and neighborhood to settlements and infrastructure, as the output results of both programs are influenced to more than 60% by these two factors (see Fig. 2). This result goes in hand with previous studies like Parisien (2009, 2012), Massad (2012) or Renard (2011). Random Forests ranks the distance to buildings (r=300m) higher than MaxEnt; however, this value strongly correlates with population density. The greatest difference between the model results is in the role of forest type. While MaxEnt ranks it on the 3th position, randomForests completely discarded this factor (only position 11 on its model buildup). The topographic parameters also seem to work contrary on both algorithms: Random forests prefers the altitude (position 6) and finds no useful information within the aspect layer, MaxEnt ranks the aspect on position 5. In both models, the importance of the density of roads, forest roads and hiking paths was comparetively minor. Details on the results are found in Arpaci et al. (2014).

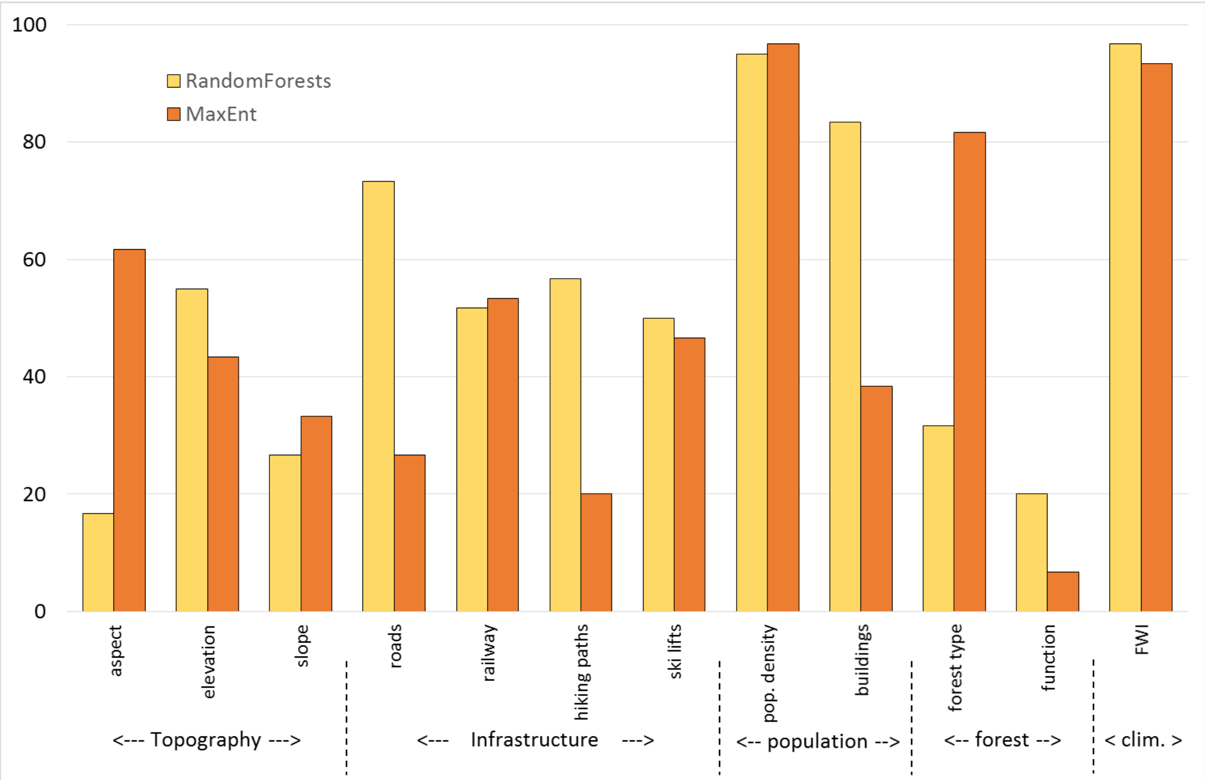

Fig. 2: Importance of the twelve input parameters for forest fire distribution (relative scale)

Combining information on fire weather, vegetation, topography and socio-economic risk factors using the results of the MaxEnt and randomForest approaches allowed us to create fire susceptibility maps for Tyrol. In these maps, each cell is assigned a percent value that describes the fit between the spatial configuration of all historic events used for training the model and the spatial configuration from cells with no known fire events. We reclassified the predictions from fire susceptibility percentage into six susceptibility classes. Figure 3 (a, b, c, d) shows the different fire susceptibility maps predicted by randomForests (a,b) and Maxent (c,d) for Tyrol; with the insets b and d showing a more detailed overview of the Innsbruck region including fire locations. It becomes clear that the highest fire hazard is concentrated along the main valleys due to a superposition of climate (higher temperature, less precipitation) and proximity to population and infrastructure. Apart from this clear result, relatively high fire susceptibity is modelled for the Upper Inn Valley and its tributary valleys which is due to the comparatively low precipitation and high number of dry foehn days. In East Tyrol, the modifying role of topographic aspect can be observed in some of the east-west running valleys. The models agree in most parts; deviations derive from the fundamentally different calculation algorithms of both programs. For presentation (fire hazard map for Tyrol according to present-day conditions), the mean of both results was used.

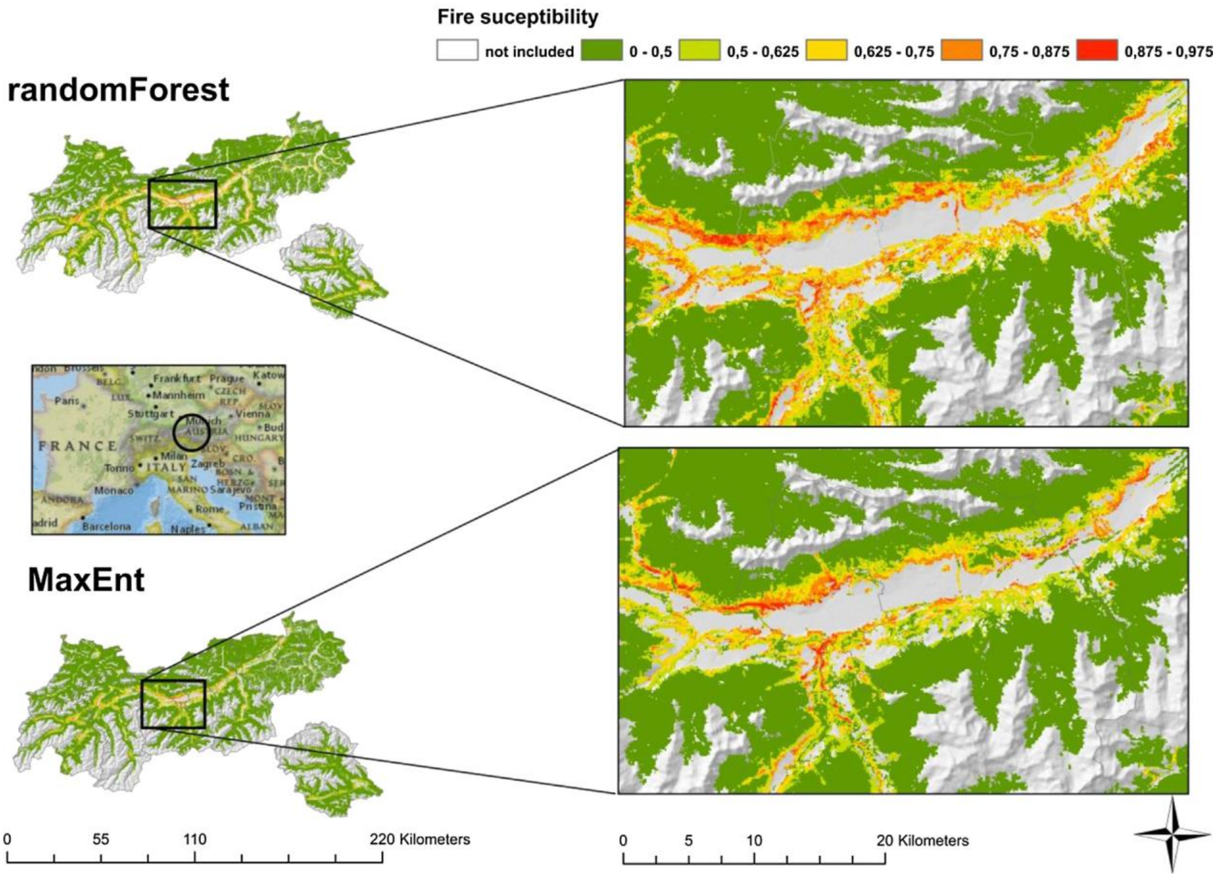

Figure 3: Fire susceptibility maps (focused on the detail area around Innsbruck) derived from randomForest and MaxEnt (Arpaci et al. 2014, Applied Geography).

The map allowed us to identify areas with a high probability of fire ignition. In combination with a map of **forest types** comprising the most relevant fuel types it was possible to evaluate the impacts of forest fires on current vegetation cover. Furthermore, we compared the actual vegetation with the potential vegetation to reveal possible differences. It has to be pointed out that the map of the potential forest association is referring to site and meteorological conditions, is not considering the actual vegetation and is currently only available for about 50% of Tyrol. About 500 fire susceptibility hotspots were taken into account. Looking at the results we can clearly see that there is a difference between the shares of the actual and potential vegetation. The dominance of spruce forests in the actual vegetation within hotspots (> 80%) is shifting to a dominance of European beech stands (> 50%). While spruce and pine stands have been the most affected considering the actual vegetation they are losing their dominance at potential sites. This shows, that many of the broadleaved dominated sites are currently covered by secondary coniferous forests, which are heavily impacted by forest fires. Considering the changing environmental conditions it would be recommendable to change species composition from coniferous stands to more broadleave dominated stands. This would not only increase site productivity and stand stability, but would reduce fire ignition probability as well.

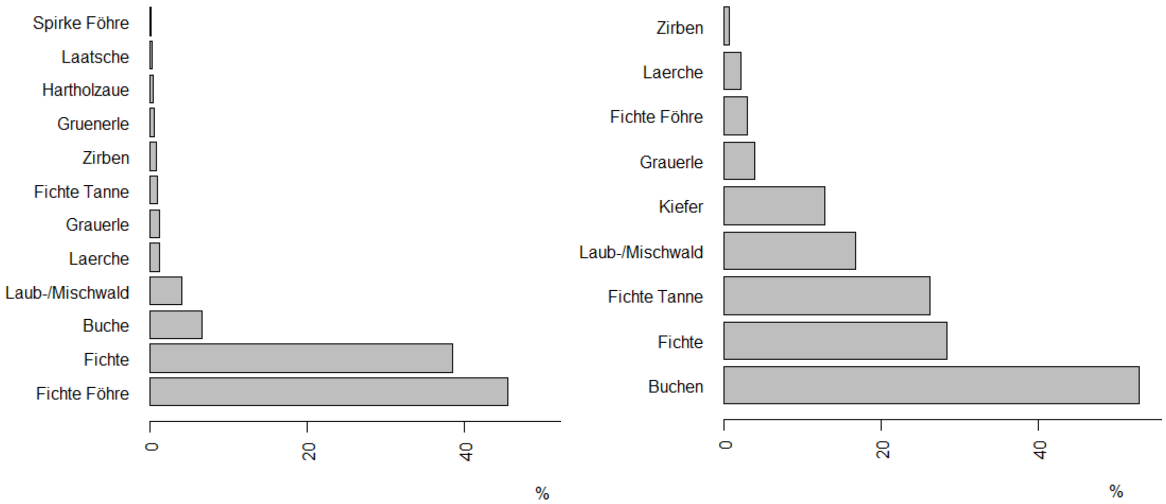

Figure 4 left: Percentage of actual vegetation in fire hot spots; right: percentage of potential vegetation in 50 % of the tyrolean fire hotspots.

Meteorological factors play a key role in affecting wildfire occurrence and behaviour. In Figure 5, the number of days with high fire risk in summer (April – November) for the last standard reference period (1981 – 2010), the beginning of this century (2011 – 2040), the middle of this century (2036 – 2065) and the end of this century (2071 – 2100) is shown. The maps show high fire risk in inner alpine dry valleys such as the Upper Inn Valley and a lower risk in northeastern Tyrol and in areas of medium to high elevation under past climate conditions (1981 - 2010). However, the risk of forest fires will spread to areas of medium elevation in the next 30-year period and to even higher elevation areas at the end of the century. The general pattern of fire risk in Tyrol (higher fire susceptibility along the valleys and in the Upper Inn valley) will remain widely unchanged; instead, the fire danger will increase in a consistent way. However, this consistent increase means that the extensive forest areas of the Lower Inn region which are scarcely affected by fire at present, will probably shift to appreciably higher susceptibility in the future.

Using the random forest model with the inputs from the **climate change scenarios** (REGCLIM and ALADIN Ensemble data) allowed us to compare possible variations in spatial fire susceptibility. There was no drastic change with regard to a high increase in fire hotspots found comparing the model outputs for past and future climate variables. Nevertheless, these results should be taken carefully into account. The future scenarios do not assume a (more than likely) increase of human settlements and infrastructure, a factor which proved to be of very high importance. Nor do they include higher vulnerability to natural disturbances of existing forest structure due to climate change. These higher fuel loads caused by wind breakages or bark beetles can lead to an increase in fire severity. These linkages have been repeatedly reported from North America and could lead to similar situations on a large spatial scale.

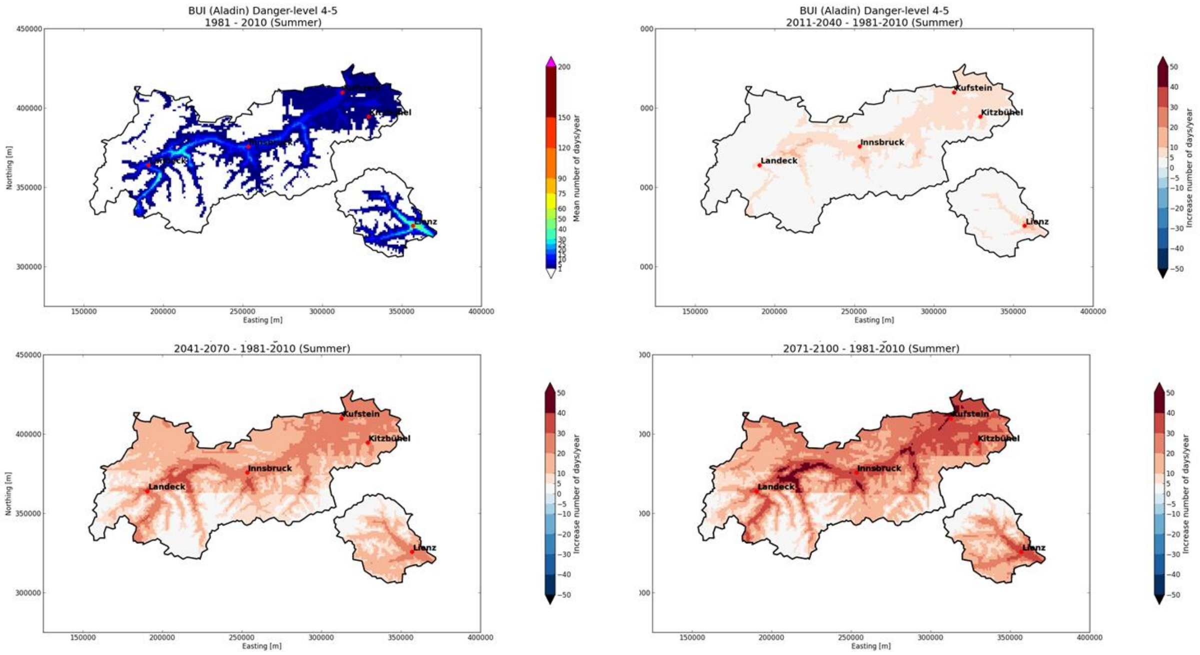

Figure 5: Development of days in summer period of BUI in danger class 4 or higher. The periods are 1981 – 2010 (top left), 2011 – 2040 (top right), 2036 – 2065 (lower left), and 2071 – 2100 (lower right). The climate model used is ALADIN.

The results of the vegetation mappings were compiled to derive timelines of **forest recovery** (Fig. 6). It becomes evident that the time required for recovery is extremely different depending on site characteristics. Woodland vegetation was reduced from 60-100% before the fires to 0-30% shortly after the fires (Fig. 6, dotted lines at the left edge). After the respective fires, regeneration seems to proceed at a maximum rate of approx. 10% increase of woodland coverage every 10 years (e.g. Unterried, Kraftwerk Vomperloch). On the longer term, the slopes Innerzwain and Hagler show regeneration rates of 5% per decade. However, at some very large sites no regeneration at all occurred (e.g. Schartlehner, Arnspitze, Brunnstein, Gimbach). On the longer time scale, it appears to be probable that regeneration on these sites could accelerate rapidly after a few decades (note the curves of Herzwiese and Bajazzbrunst); at Herzwiese, this process was promoted by reforestation measures in a time period of moderate avalanche activity. The sites Hagler and Gimbachtal were thrown back in their development by a second fire on each slope (dotted lines).

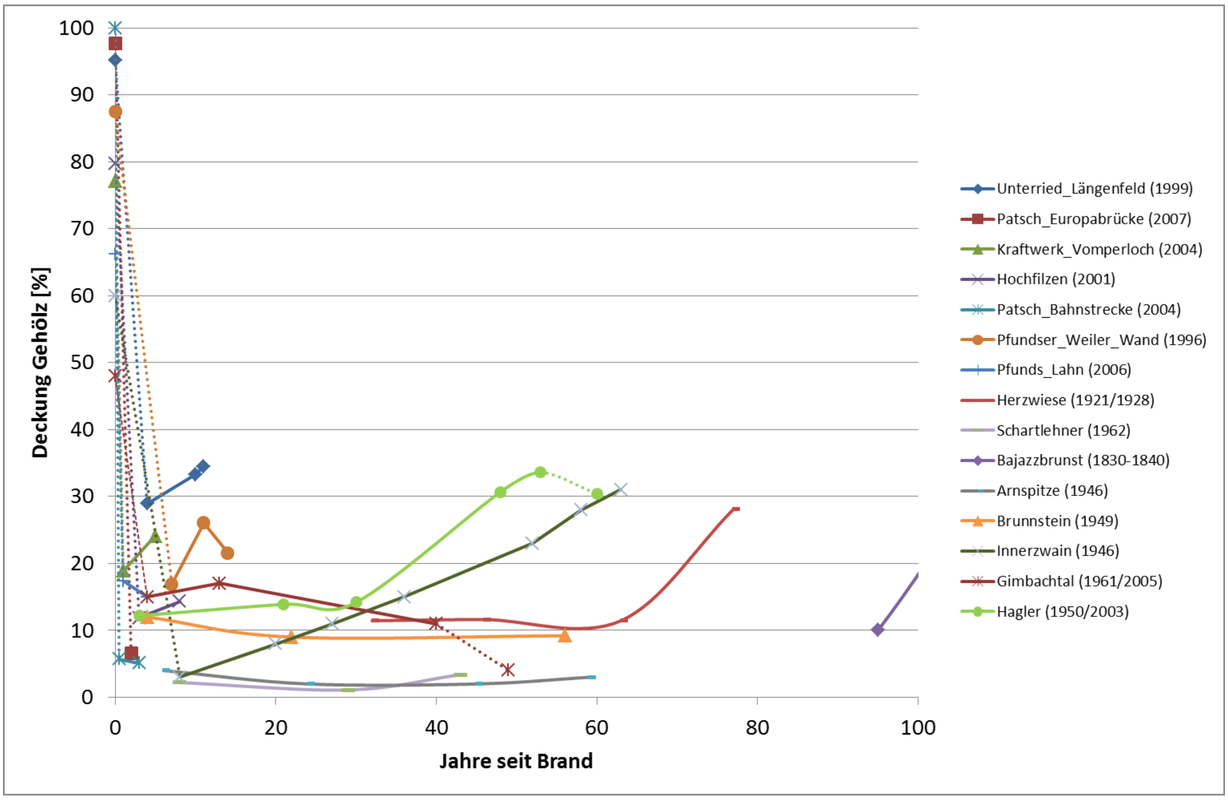

Fig. 6: Recovery of woodland vegetation after forest fire for 13 different slopes

The parameters governing the divergent development on different slopes were investigated using a multi-parameter GIS analysis based on 10 x 10 m raster cells. The influence of the parameters elevation, aspect, slope, rock type, different neighbourhood parameters, and the elapsed time since the fire were considered. Figure 7 shows the results; positive values indicate a fostering influence of the respective factor for regeneration, negative values an inhibiting effect, while values near zero indicate that the factor is relatively unimportant. Surprisingly, the time after fire seems to be of minor importance for recovery as even retrograde development (ongoing degradation with time) can sometimes be observed. Forest regeneration is inhibited by higher elevation and higher slope angle while alpine shrubs (‘krummholz’) are not sensitive towards these factors. Recovery of all types of vegetation is consiberably slowed down in furrows; the supposed positive effect of higher moisture availability and greater soil depth is obviosly over-compensated by stronger geomorphic activity in these areas. Neighbourhood to forested pixels and distance to the edge of the burnt area do not influence forest regeneration significantly. Regeneration of krummholz and forest is facilitated on north-exposed slopes compared to south-exposed ones (probably because of moister micro climate); dolomitic bedrock supports grass vegetation while woody vegetation prospers better on limestone.

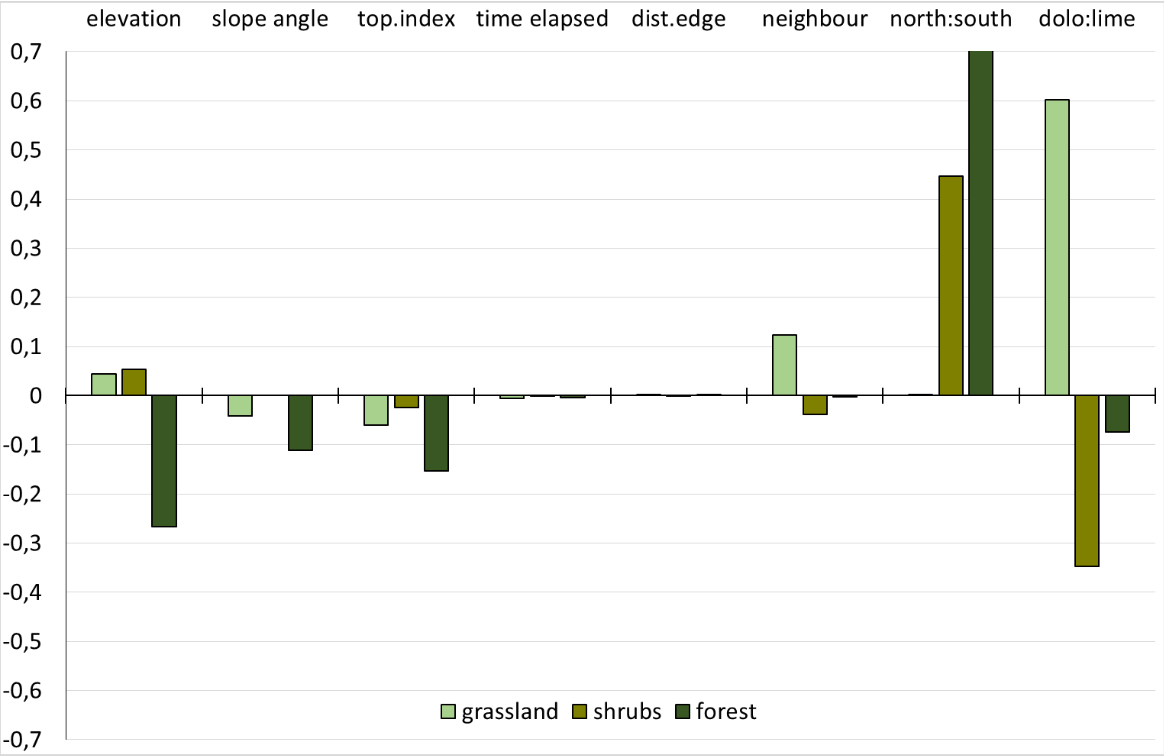

Fig. 7: Relative importance of different factors for vegetation recovery; results of a logistic regression analysis including >100,000 raster cells on 26 forest fire sites. Negative and positive values indicate inhibiting and fostering influence, respectively (Sass & Sarcletti, in prep. / Journal of Wildfire Research).

For assessing the impact of **post-fire natural hazards**, the number of affected buildings for three intensity classes were determined for avalanches and rockfalls, respectively. Only full deforestation was taken into account for avalanches while in the case of rockfalls, three different forest scenarios were considered. Regarding rockfall intensity, the calculated forest scenarios do not seem to have considerable effect. However, the influence of the forest becomes more obvious when the number of deposited rocks and the number of passing rocks are considered. The number of affected buildings remains fairly constant while the number of deposited rocks as well as the number of passages increase with decreasing forest densities. This implies that the overall intensities and the number of affected buildings do not increase significantly in case of deforestation while the probability of harmful events grows.

The calculated damage values consist of the objects price itself as well the value of its inventory. The consequences for human lives are not regarded due to missing data on the frequency of visitors, people living in the buildings etc.. The damage functions for the inventory were designed to be generally smaller than the those for the building structure; i.e. the inventory may remain undamaged even when the buildings are damaged. The maps shown in Fig. 8 and 9 give an overview of all the investigation sites and the respective losses for each hazard process. Classified monetary losses are assigned to the investigated sites and to single objects. It is evident that the damage potential is higher in the western region of Tirol, which is clearly shown in the case of avalanches and to a smaller degree for rockfalls as well. The total potential loss for the 17 study areas in case of a 150-yr avalanche is 108.7 M€ which amounts to a yearly risk of 724 T€/yr. For rockfalls, the total loss in a worst case scenario is 87.1 M€; the risk per year is hard to predict as the return interval of the considered large boulder falls is unknown. In case of an estimated 500-yr return period the risk is 174 T€/yr. It is important to note that these are maximum values and that total deforestation is not very likely. More realistic ranges are 200 – 500 T€/yr for avalanches and 50 – 100 T€/yr for rockfall. On the other hand, more than 90% of Tyrol have not been considered in this calculation and thus, a total damage of far more than 1 M€/yr due to secondary effects of forest fires appears to be realistic.

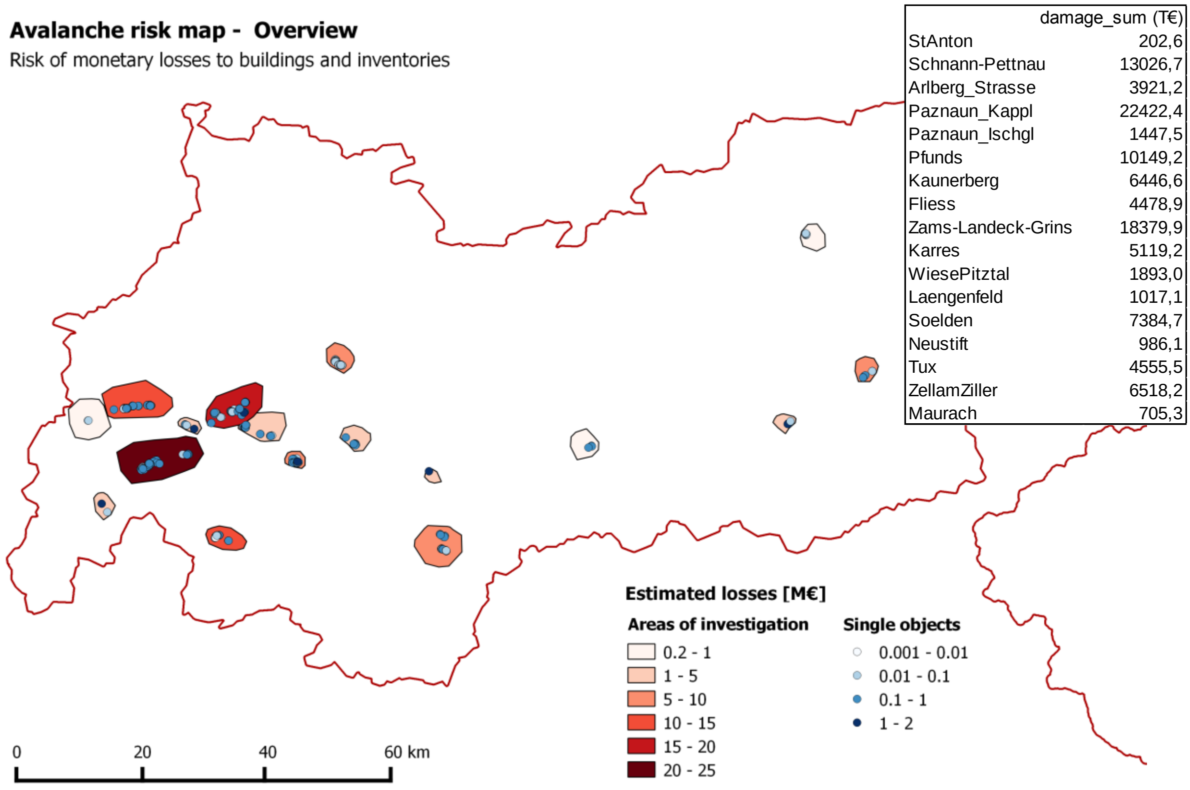

Figure 8: Possible monetary losses in the 17 case study areas in case of a 150-yr avalanche event after fire-driven deforestation.

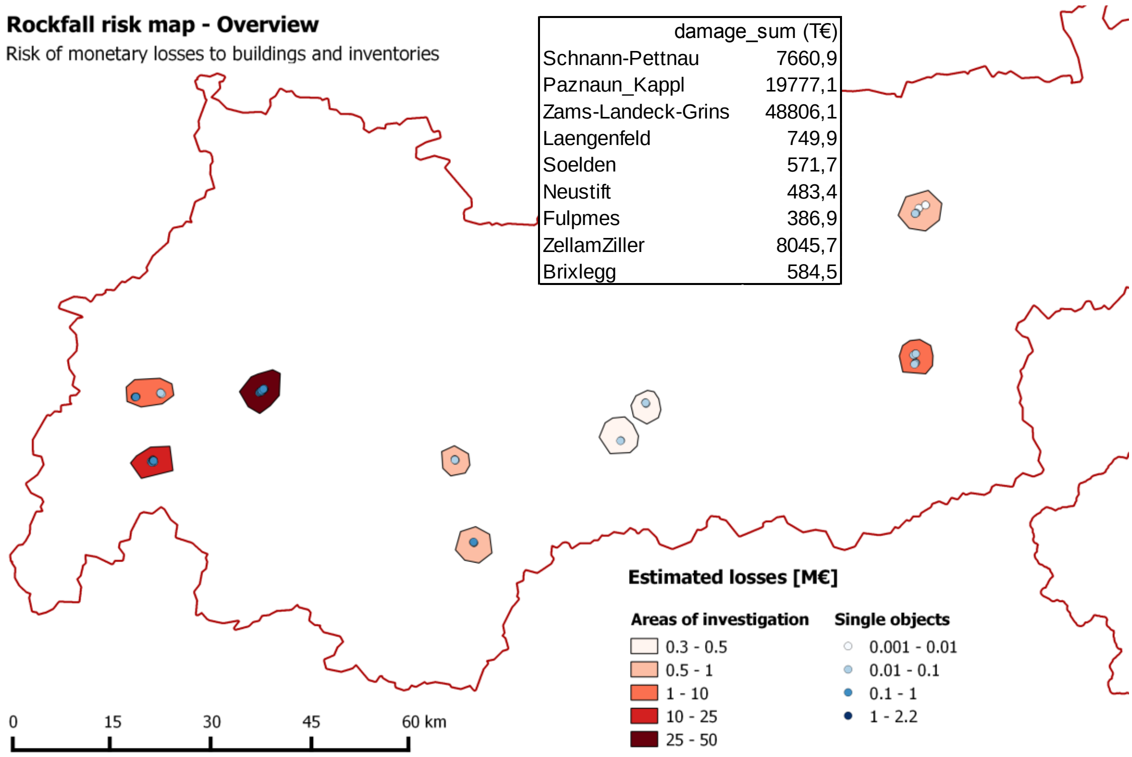

Figure 9: Possible monetary losses in the nine case study areas in case of worst-case rockfall event after fire-driven deforestation.

5 Schlussfolgerungen und Empfehlungen

The following conclusions have been drawn from the project results:

- The majority of documented forest fires had a size around one hectare and were ignited due to anthropogenic reasons (74%). Spring and summer are the main fire seasons; the secondary peak in summer has increased during the last decades. Recently, 20% of the forest fires in Tyrol were ignited by lightning. The major portion of forest fires is ignited at south facing slopes.

- Coniferous forests are mainly affected by fires with the majority in Norway spruce (*Picea abies*) forests (39%), followed by Pine (*Pinus sp.*) forests with 26%. In many places, these forest communities are not the potential natural vegetation. A forward-looking shift towards mixed or broadleaf forests might reduce fire susceptibility.

- The most important factors governing the spatial distribution of forest fires are climate (i.e. mean duration of critical fire weather conditions) and neighborhood to settlements and infrastructure. The output results of both applied machine learning algorithms (MaxEnt and RandomForests) are influenced to more than 60% by these two factors. Vegetation, topographical aspect and elevation are further important parameters (however, subordinate to climate and population).

- The highest potential fire hazard is concentrated along the main valleys due to the superposition of climate (higher temperature, less precipitation) and proximity to population and infrastructure. Apart from this clear result, relatively high fire susceptibity is modelled for the Upper Inn Valley and its tributary valleys which is due to the comparatively low precipitation and high number of dry foehn days.

- Potentially dangerous fire weather conditions will become more frequent towards the middle and the end of the 21st century. The general pattern of fire risk in Tyrol (higher fire susceptibility along the valleys and in the Upper Inn valley) will remain widely unchanged in the future; however, the risk of forest fires will spread to areas of medium elevation in the next 30-year period and to even higher elevation areas towards the end of the century. This consistent increase means that the extensive forest areas of the Lower Inn region will probably shift to appreciably higher susceptibility in the future.

- The time required for recovery after fire is extremely different depending on site characteristics. The elapsed time after fire seems to be of minor importance for recovery as even retrograde development (ongoing degradation with time) can sometimes be observed. Forest regeneration is inhibited by higher elevation and higher slope angle and is consiberably slowed down in furrows. Neighbourhood to forested pixels and distance to the edge of the burnt area do not influence forest regeneration significantly. Regeneration is facilitated on north-exposed slopes compared to south-exposed ones; dolomitic bedrock seems to be particularly adverse to woodland vegetation.

- The total potential loss for the 17 study areas in case of a 150-yr avalanche is 108.7 M€ which amounts to a yearly risk of 724 T€/yr. For rockfalls, the total loss in a worst case scenario is 87.1 M€; the risk per year is hard to predict as the return interval of the considered large boulder falls is unknown. In case of an estimated 500-yr return period the yearly risk is 174 T€/yr.

The main target group to benefit from the results of the project are forest managers on different organisational levels. Knowledge on the spatial patterns of fire susceptibility and the potentially endangered areas is helpful to enhance the awareness of local foresters as well as of local people. The disparity between the potential forest types and the actual tree species (Fig. 4) is an additional stimulus for forward-looking adaptation measures on the regional scale (shift towards broadleaf and mixed forests). The most relevant handbook concerning silvicultural guidelines in Austria is the 'Waldtypisierung' which is currently being established. This handbook of practice for the local foresters allows to identify relevant characteristics about all forest types like climatic condition, location, soil, geology, vegetation, growth and yield parameters, natural dynamics and management prescriptions (e.g. tree species recommendations, tending concepts). As a basis for the guidelines the present actual condition (current vegetation) and the desired future conditions are used, which are derived from the PNV (potential natural vegetation) and special forest functions (e.g. protection against avalanches, rock fall). The mapping of potential forest types is done with a GIS supported geo-ecological model which allows a classification of forest types based on digital geo-ecological parameters (e.g. height above sea level, substrate, land form, inclination).

An example is provided in the annex. Based on the map of the forest type classification and the analysis of the future fire danger conditions the management recommendations for selected forest types were given. The FIRIA results will be fully implemented in the course of the following few years when the information on the most important forest communities will be updated.

Municipalities and local communities are the second target group which will benefit from the hazard maps produced. The maps are an instrument for rising the awareness of the most endangered forests in the respective districts and provide a clear picture of the infrastructure at risk in case of fire-driven deforestation. However, these results are still preliminary because the underlying scenarios (i.e. complete deforestation by fire) are a worst-case assumption which is not fully justified and realistic. Refining the results in a follow-up project is necessary before recommendations should be forwarded to the stakeholders.

C) Projektdetails

6 Methodik

Full details on the methodology and the work performed are provided in section 4. Here is a short overview of the methods applied:

- Data collection took place by merging two different already existing databases. Further forest fires were added to the database by searching through additional sources (archives, chroniclers, commemorative books, personal meetings with local persons). The fires used for modelling were located as exactly as possible by investigating available photographs, aerial pictures, local place names and topography and by consulting involved firemen or reporters.

- Necessary background data was integrated it a GIS working space using a congruent projection system. The map data was drawn from various sources sources (TIRIS Tyrol, BFW Austria, Statistik Austria, partly supplemented by Open Street Map). Completion and falsification of all input data, deleting double line elements, merging roads and hiking trails and transforming the projection into one system had to be carried out. The data files were used to calculate an Euclidian distance raster and a density raster file for each map. One homogeneous forest layer was created out of five different. Zonal statistics for every single forest-polygon wer calculated.

- We used two multivariate data mining techniques (MaxEnt and randomForests) in parallel to calculate the contribution of various input data on forest fire distribution. Twelve parameters were finally selected for the modeling process (see Table 1 in section 4). Using a non-parametrical statistical method we selected the best suited fire weather index (FWI) for the prediction of forest fire danger in Tyrol.

- Three climate scenarios from the regional climate-models (RCMs) ALADIN, RegCM3 and REMO were bias-corrected and localized to a finer resolution. Bias-correction for each RCM was performed using a quantile mapping technique based on the E-OBS data set. The localization was done by superimposing local climate patterns obtained from the 1 km x 1 km resolution INCA data set to the RCM. Various model parameters, including temperature, precipitation, and relative humidity on a daily basis for the period 1951 – 2100 on a 1 km x 1 km grid for Tyrol were generated.

- We carried out mapping of vegetation on slopes of varying age after fire from ortho images and personal inspection; the development over time was investigated using sets of historical aerial photos from different years to derive timelines of tree regeneration. In order to clarify the influential factors contributing to the observed regeneration patterns, we performed a GIS-based, multinomial logistic regression. This approach belongs to the group of Generalized Linear Models (GLM).

- Fuel data was collected directly in the field from 57 sample plots all located in the vicinity of previous fire sites. Selected case studies were simulated using known fire data and fuel models, results indicated the rate of mortality and hence the loss of protective functions.

- Hazard assessment was carried out in a two-step procedure starting with regional models and later focusing on field investigations and data collection for local models. The rockfall model Rockyfor3D version 5.1 and the avalanche model RAMMS version 1.5 were used. For rock fall modelling, the input parameters for Rockyfor3D were collected in the field. For avalanche modelling, avalanche release areas were determined for each hazard spots. Punctional information on public services was pooled into six categories. The degree of actual damage and the associated monetary loss was derived from guidance values after Heinimann (1999).

7 Arbeits- und Zeitplan

Data collection, merging the different databases and preparing all input parameters for fire susceptibility modelling were carried out in the first approx. 18 project months. This work package (WP2/3) had to be terminated in time because several further steps could not start before this preparatory work was finished. Fire Weather Index calculations, fuel load modelling and vegetation surveys of forest fire sites from aerial photographs were carried out parallel to data collection (WP3). Modelling fire susceptibility (WP4) using the machine learning algorithms MaxEnt and randomForests took the next approximately six months (joint work of Uni Graz and BOKU).

Only after these steps had been finished, we could start modelling post-fire natural hazards (WP6) starting from the forest fire 'hot spots' derived from WP4. This work package roughly took the last project year. The scenarios of future climate susceptibility (WP5) were calculated between the second and third project year which took c. six months (with some necessary interruptions in the joint workflow).

8 Publikationen und Disseminierungsaktivitäten

Publications:

- Vacik, H. & Müller M. (2013): Waldbrand-Datenbank für Österreich, Zeitschrift für Wildbach-, Lawinen-, Erosions- und Steinschlagschutz (77 Jg., Nr. 172, 188-189.
- Leidinger D.; Formayer H.; Arpaci A. (2013): Analysis of current and future fire weather risk in Tyrol. [Int. Conference on Alpine Meteorology (ICAM), Kranjska Gora, 3. - 7. Juni 2013] In: ICAM, 32nd Conference on Alpine Meteorology, 3-7 June 2013, Kranjska Gora, Slovenia, "Book of Abstracts"
- A. Arpaci, B. Malowerschnig, O. Sass & H. Vacik (2014): Using multi variate data mining techniques for estimating fire susceptibility of Tyrolean forests, Applied Geography 53: 258-270, http://dx.doi.org/10.1016/j.apgeog.2014.05.015. (pdf in the annex).
- Malowerschnig, B. & Sass, O. (2014): Long-term vegetation development on a wildfire slope in Innerzwain (Styria, Austria). Journal of Forestry Research 25: 103-111.
- Vacik, H., Arpaci, A. & Müller, M. (2014): Monitoring der Waldbrandgefahr in Österreich und anderen Alpenländern - Monitoring of forest fire risk in Austria and other Alpine countries Zeitschrift für Wildbach-, Lawinen-, Erosions- und Steinschlagschutz (under review)
- Arpaci, A. & Vacik H. (in progress): Development of fuel models for different fire prone vegetation types of the Austrian Alps.
- Sass, O., Sarcletti, S. (in progress): Spatial patterns of vegetation recovery after forest fires on steep mountain slopes in Austria.

Presentations at external events:

- Sass, O., Vacik, H. et al. (2011): The FIRIA project: Fire Risk and Vulnerability of Austrian Forests under the Impact of Climate Change (Poster). Managing Alpine Future, Innsbruck, 21-23 Nov 2011.
- Leidinger, D., Formayer, H. (2011): Vorläufige Ergebinsse der Projekte ALP FFIRS, AFFRI & FIRIA (Poster). 4. Österreichischer MeteorologInnentag, Klagenfurt, 3-4 Nov 2011.
- Cane D., Arpaci A., Barbarino S., Vacik H., Valese E., Rizzolo R. (2011): An approach for the evaluation of fire weather indices in the Alpine Space: preliminary results. In: Working on Fire (Eds.): Living with Fire, Adressing Global Change through Integrated Fire Management, www.wildfire2011.org
- Müller M., Formayer H., Diendorfer G., Arpaci A., Gossow H., Vacik H. (2011): Analysis of lightning induced forest fires in Austria . In: Working on Fire (Eds.): Living with Fire, Adressing Global Change through Integrated Fire Management, http://www.wildfire2011.org/
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- Arpaci, A, Vacik, H, Sass, O, Sailer, R (2012): Fire risk and interactions with other natural hazards under the impact of climate change in Austria (Poster). In: Global Risk Forum, GRF Davos, International Desaster Reduction Conference IDRC, Davos, Switzerland, "Integrative Risk Managment in a changing world - Pathways to a Resillient Society" Programme & Short Abstracts.
- Cane D., Arpaci A., Conedera M., Barbarino S., Vacik H., Valese E., Pezzatti G.B. (2012): Suitability of different Fire Weather Indices for alpine conditions: an extensive evaluation with high resolution data (Poster). EGU General Assembly, Vienna, 20 Apr 2012.
- Sass O., Vacik H., Arpaci A., Malowerschnig B., Formayer H., Sailer R. (2012): Das FIRIA Projekt: Beurteilung der zukünftigen Waldbrandgefährdung in Österreich (Poster). Österr. Klimatag 2012, Vienna, 14 Jun 2012.
- Sass, O., Malowerschnig, B., Stöger, F. (2012): Regeneration und Goeomorphologie-Ökologie-Interaktionen auf Brandflächen der Nördlichen Kalkalpen (oral pres.). Jahrestagung des AK Hochgebirgsökologie 2012.
- Müller, MM; Gossow, H (2013): A new forest fire database for Austria: data collection, explorative analysis and public awareness as basis for future forest fire research. Mountain Days, JUN 11-13, 2013, Mittersill, Salzburg, Austria.
- Malowerschnig, B.; Sass, O. (2013): A high-resolution modelling approach on spatial wildfire distribution in the Tyrolean Alps (Poster). EGU 2013 General Assembly, Vienna, 9 Apr 2013.
- Malowerschnig, B.; Sass, O. (2013): Modelling the spatial distribution of wildfires in the Tyrolean Alps (Austria) under current and future climate conditions. International conference on forest fire risk modelling and mapping, 30th Sept. – 2nd Oct. 2013, Aix en Provence (France).
- Sass, O. (2014): Wälder in Flammen. Invited lecture at the Gemeindemuseum Absam (Tyrol).