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Alteration of the alpine vegetation due to climate change in the Karwendel Alps, Tyrol, Austria

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Author's declaration

No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

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ABSTRACT OF THESIS submitted by:

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Climate change is indeed a serious problem across most of the planet. However, certain areas, such as the Alps, are affected at a higher rate. The very unique alpine regions, which provide habitats for 20-25% of Europe's vascular plants (BMU 2007), may particularly be impacted. Therefore, the thesis aims to investigate the direct effects of climate warming on the alpine vegetation's distribution in the Karwendel Alps, Tyrol, Austria. Here, a site was selected where the higher situated flora belts were studied in order to map recent patterns, which were compared to the previous stages of the vegetation. Based on the obtained data, a model was constructed to show the future plant species distribution regarding two different climate scenarios by 2050. The results indicate that the timberline species and the grasslands will probably spread and invade the higher located vegetation zones of the dwarf shrub and alpine species, which may experience significant habitat reduction. Some of these species, which have social and ecological relevance, as well, may also face the potential of extinction unless certain steps are taken to preserve them for the future generations.

Keywords: climate change, alpine vegetation, *Pinus mugo*, Karwendel Alps

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1. Introduction

1.1. Background and importance

Climate change is indeed a problematic and accelerating issue that impacts our whole planet, although the level of its effect is not evenly distributed. Certain areas, including the more temperature fluctuation-sensitive mountain regions, are affected at a more significant rate suffering severe degradations in their various and valuable functions (Beniston 2003). As the UN Rio Conference summarized in Agenda 21 in 1992:

> "Mountains are important sources of water, energy, minerals, forest and agricultural products and areas of recreation. They are storehouses of biological diversity, home to endangered species and an essential part of the global ecosystem…Most mountain areas are experiencing environmental degradation"(UN 1992),

which is partially attributed to climate change (BMU 2007). For instance, in the vulnerable regions of the Central European Alps, the results of global warming are especially accentuated and evident affecting numerous environmental, social and economic aspects (e.g. agriculture, tourism, water and energy supply, mountain biodiversity) (Theurillat & Guisan 2001; Beniston 2003; BMU 2007; CIRCLE 2008).

In the Alps, one of the most rigorously influenced issues by climate change is its unique ecosystem. Some extremely specific and vulnerable species that are used to unique living conditions are majorly threatened by the projected radical temperature variation (Haeberli and Beniston 2005; Aerts et al. 2006; Holzinger et al. 2007). Here, plant species and related organisms already have limited habitat, which is shrinking year by year due to temperature increase and land use change (Theurillat and Guisan 2001). However, with an even more altered environment, they might be sentenced to more excessive habitat loss or even to extinction, while other species may expand their territories (Pauli et al. 1999; 2001; 2003; Parolo & Rossi 2008; Watkiss et al. 2004). All in all, by the end of this century, if temperature rise continues, more than 60 % of the vascular plants of the alpine vegetation, including numerous endemic and highly specialized species, may be endangered (Grabherr 2009).

As a result, in the Alps, it is particularly vital to observe, monitor and predict the intensity of global warming and its potential outcomes to mitigate or even avoid them now and in the future. This is chiefly important for those alpine countries, e.g. Austria, which are severely impacted, and, despite the major level of probable consequences, still do not possess a National Climate Change Adaptation Plan, that would serve as a guideline for describing necessary actions for adaptation and mitigation strategies addressing climate change (CIRCLE 2008). Within these strategies, it is essential to tackle the problem of the alpine ecosystem, as well. The response of the alpine vegetation to climate alterations therefore should be identified and projected in order to allow planning of key activities in biodiversity conservation strategies.

1.2. Main aim and objectives

In the European alpine region, the 1-2^{o}C increase in air temperature of the last century (Haeberli and Beniston 1998) most probably had an impact on the sensitive alpine vegetation (Beniston 2003). Hence, the main aim of the thesis is to reveal in what way mountain plant species' distribution have responded to this temperature change, and based on this, to model how their occurrence might be shaped by climate alterations in 2050 in order to aid conservation strategies. To study this phenomenon a site in Hafelekar, Karwendel Alps, Austria was selected. Here, the higher and more temperature-sensitive belts of the alpine vegetation were mapped and compared to previous stages of the vegetation in order to describe the future response of the alpine plant species to temperature increase.

The objectives of the thesis include:

- determining the temperature trend of the last century until now in the proximity of the site in order to relate the level of vegetation modifications to temperature change
- the analysis of other physical factors (e.g. slope angle)
- the investigation of the timberline location and the forested area currently and 60 years ago
- the comparison of the recently existing and in the beginning of the 20^{th} century's recorded species with the aim of spatial and temporal variability detection about vegetation patterns
- the projection of the probable distribution of the vegetation by 2050 with the assistance of the above mentioned goals
- and finally, the evaluation of what sorts of modifications can be generated in the ecosystem by the potential alterations and what conservation workers can do to save certain alpine species.

1.3. Indication of the approach

In order to understand historic vegetation and climate change dynamics of the location various sources were utilized:

- the procession of long term temperature data of the nearby meteorological stations was carried out to detect whether temperature increase was in fact significant at the site
- the microtopography and the macrotopography analysis on the field and by remote sensing data
- remote sensing data and historic records of the site's vegetation were evaluated with the focus on the timberline's position and the occurring species
- fieldwork was conducted to study vegetation characteristics, e.g. species richness and coverage

Based on the obtained vegetation, slope gradient and temperature data, a model was constructed to project potential alterations of the major plant belt's distribution in 2050 using two distinctive climate scenarios.

1.4. Outline of the thesis structure

The thesis firstly presents an insight into the rate of climate change and its generic consequences on our planet as well as specifically on the Alps and Austria, and introduces the major literature on the alpine vegetation's major characteristics, importance and its response to temperature variation. This is followed by the methodology section and the results of both the secondary and the fieldwork data. The discussion reviews how plant species distribution is altered on this certain area and, whether it is clearly related to climate change or not. Also, the projections of the future extension of the alpine floral zones are assessed with reference to some wider implications. The last part of the thesis summarizes the main findings and provides some recommendations for potential conservation plans.

2. Overview of climate change and its effects on alpine vegetation

2.1. Introduction

Based on existing literature, this section presents the generic consequences of climate change both in the European Alps and in Austria. The response of alpine vegetation to climate change, mainly concerning tree line dynamics, nival vegetation modifications and snowbed communities' sensitivity, is also presented here. Besides, a description of the major driving factors of vegetation patterns will be provided. Furthermore, this part will review several predictive vegetation models and their aspects in addition to the discipline gaps in current research. Finally, the practical implication of vegetation dynamic research in terms of climate change will be discussed.

2.2. Climate change and its generic consequences

Global warming has reached an unprecedented high level in the last thirty years mainly due to human activities via emitted greenhouse gases (GHG), chiefly CO_2 (Aerts et al. 2006; Kuynlestierna and Panwar 2007). As a result of intensified global emissions the average atmospheric temperature of our planet rose by 0.74^{o}C in the past century and its increase is projected to be between 1.8 and 4^{o}C by 2100 (Kuynlestierna and Panwar 2007). This worldwide human-induced growth in temperature affects to a certain extent most of our planet causing various alterations in the environment and in society (IPCC 2007). Climate change already has and will continue to generate the warming and the acidification of the oceans, sea level rise, modification of precipitation patterns and thus higher occurrence of weather extremes including droughts and storms, shrinkage of glaciers, ice and snow cover, melting permafrost, which trigger further changes in freshwater quantity and quality, erosion rate, spread of vector diseases and alteration of species richness and distribution (Houghton et al.

2001; Kuynlestierna and Panwar 2007). As a result, it is evident that global warming modifies the amount and features of essential segments of life including water, food and health security, which also has apparent effects on millions of human lives (Kuynlestierna and Panwar 2007). However, these impacts of climate change are not equally distributed and particular areas, such as high mountain regions including the Alps, are more sensitive and constitute the most vulnerable places on Earth (Theurillat & Guisan 2001; Beniston 2003; Dirnböck et al. 2003; CIRCLE 2008).

2.3. The level of climate change in the European Alps

The importance of high altitude regions, like the Alps, is indisputable. Nonetheless, their degradation is continuous partially due to climate warming. In the last century, this was characterized by an increase of approx. $2^{o}C$ of minimum temperatures, a less significant, but clearly increasing trend in maximum temperatures and a more modest variation in precipitation meaning higher intensity in winter and drier periods in summer (Haeberli and Beniston 1998). There were two marked higher peaks in temperature rise in the 20^{th} century, the first during the 1940's, which was followed by a general cooling in the 1950's, and an even broader, more dynamic warming since the 1980's (Beniston 2005). The rate of this major temperature increase in the last 30 years has approximately doubled that of the first warming peak, and is regarded as the greatest amplification of warming in the millennia with an average $1\text{-}2^{o}C$ amplified change depending on the location of the sites (Haeberli and Beniston 1998; Aerts et al. 2006). Although these temperature variations are already substantial and highly impinge on the surrounding environment, climate scenarios predict an even more remarkable rise with an estimated $1\text{-}4.5^{o}C$, in the worst case an approximate $6^{o}C$ by 2100 (Gyalistras 2005), compared to which the level of the recent warming can be considered relatively minor (Houghton 2001; Aerts et al. 2006). Nonetheless, such 'minor changes' have already largely impacted the Alps, having especially pronounced effects on the high mountain regions (Haeberli and Beniston 1998).

2.4. The impacts of the recent warming in the European Alps

2.4.1. The cryosphere and the hydrosphere

Since the end of the Little Ice Age in the 1950's, the glaciers of the Alps have lost approximately 30-40% of their surface area and around half of their volume as a result of temperature warming (Haeberli and Beniston 1998). Some remarkably dry and hot summers further reduced the mass balances, as it happened in 2003 when 10% of the remaining glaciers melted (Watkiss et al. 2004). Snow cover and permafrost were similarly affected being limited to higher altitude due to the increase of both winter and summer temperatures and the decrease of summer precipitation. If such a tendency continues, it is most likely that the Alps will lose most of its glacier coverage within some decades, while snow limit and permafrost can move several hundred meters higher (Haeberli and Beniston 1998; BMU 2007). A significant decline of the ice cover along with the modification of precipitation patterns can cause disequilibrium in the water cycle disturbing the level of soil moisture and groundwater, generating mass movements and perturb vegetation distribution (Beniston 2003).

2.4.2. The ecosystem

Mountain regions are very important areas from a biodiversity perspective and regarded one of the most species-rich sites of the Earth providing refugia for many endemic organisms (Beniston 2003; BMU 2007; Pickering 2008). This is indicated by the fact that the European mountain systems alone host 20% of the plant species of the continent (Grabherr 2009). However, as temperature and climate-related factors are the major drivers of plant distribution in the alpine regions, climate warming and the related environmental changes have already impacted mountain ecosystems and will certainly cause more far-reaching alterations (Körner 1999; Pickering 2008; Wallentin 2008). Long-term data already show longer vegetation periods, earlier budding, reduction of the more temperature sensitive snow-bed and high alpine species, and upward migration of plant and animal species as a result of climate change (BMU 2007). Primarily due to temperature increase and the induced upward migration of the tree line, plant species extinction can reach 60% in the alpine regions taking into account the worst scenarios (Thuiller et al. 2005; Grabherr 2009). For example, in Switzerland it is projected that a 3.3^{o}C temperature rise will cause the loss of around 60-80% of the area of the more vulnerable alpine and nival vegetation belts. These plants occupy the habitats of the most elevated regions of the mountains and the peaks from where further upper migration is practically impossible (Theurillat & Guisan 2001). This process on the other hand, will mean the extended growth and upward shift of the lower vegetation belts including subalpine grasslands, which according to some studies, have already started to proceed to higher positions (Grabherr 1994; Pauli et al. 2001) along with the tree line (Wallentin et al. 2008).

Besides species distribution, climate change is likely to influence habitat fragmentation, species abundance and composition (Beniston 2003). Animal-plant interactions can also be the objects of change. For instance, particular herbivores can reduce the dispersal ability and their potential to cope with climate warming as it is showed in the case of the growing red deer and roe deer populations that support *Picea abies* by feeding on the gradually declining silver fir (*Abies alba*) (Theurillat & Guisan 2001).

2.4.3. Social impacts

Under such weather and altered environmental conditions, the potential of certain natural hazards (e.g. heat waves, avalanches, fires, landslides and floods) enhances and their combined occurrence can significantly raise the socio-economic costs of the affected countries (Beniston 2003; BMU 2007).

Also, water resources, of which abundance was taken for granted, might present declining trends due to modifications in the water cycles and the diminishing area of ice and snow coverage (Beniston 2006).

Tourism, especially winter tourism, which is an important source of revenue (50 billion Euros annually) for the Alpine countries, can be adversely affected by climate warming and reduced snow coverage (BMU 2007). According to Beniston (2003), 2^{o}C warming can decrease the number of winter sport spots providing proper ski facilities by 37%.

Human health can also be affected by climate change in many different ways in the Alps. In spite of some degree of uncertainty, ticks and their related diseases, such as Lyme disease and meningitis, are likely to expand their ranges and move towards higher altitudes as temperature increases. Moreover, most regions will experience amplified grass pollen seasons which can further enhance allergic symptoms. Occasions of weather extremes, such as heat waves or extreme cold can most probably have an effect on those, whose health is already sensitive to alterations, including the elderly and the young (BMU 2007).

2.5. The significance of the site: climate change in Austria and adaptation to it

Austria is considered to be in a particularly vulnerable position with respect to climate change as alpine areas constitute a major proportion of the country (70% of the country's surface is above 500 m and 40% is above 1000 m). The national impact scenarios forecast that most of the negative processes, which are mentioned in section 2.4, are likely to take place and be followed by additional regional-specific problems induced by climate change (CIRCLE 2008).

Probably one of the most threatening risks for Austria, where 75% of the energy is generated by hydropower plants (Austrian Energy Agency 2005), is the potential disruption of production capacity and transmission as a result of seasonal and general water volume variations and runoff extremes, which besides the power supply may influence future drinking supply (CIRCLE 2008).

Additionally, crop production areas might suffer the consequences of pronounced soil erosion, extreme drought and precipitation intensity or duration exceeding the benefits of the higher moisture level increased crop yields. Particularly higher-situated agricultural areas have to cope with more severe conditions and expanded rate of nature hazards (CIRCLE 2008).

Climate change also shapes forestry and timber activities directly with lower seedlings and lessened regeneration ability, and indirectly with more pronounced insect and disease occurrence as well as larger numbers of fire incidents (CIRCLE 2008).

Winter tourism, which contributes with an average 6% to Austria's GDP (Voase 2002) and provides working opportunities for 10-12% of the population in the Alpine region (BMU 2007), might be severely influenced by lower snow coverage rate and higher temperatures (CIRCLE 2008). On the other hand, as Beniston (2003) reveals, new recreational opportunities may rise as a result of expanded summer season.

Within the financial sector, property insurance industry is referred to as the probably most affected area by climate change. The major floods in 2002 and 2005 and the extreme hot summer of 2003 already concerned several insurance companies (CIRCLE 2008).

The Alps provide habitats for 1500-3000 species including 20-25% of Europe's total vascular plants in the territory of 3% of whole Europe (BMU 2007). These biodiversity hotspots have special importance in the country hosting some of the national symbols of Austria and Tyrol e.g., Edelweiss (*Leontopodium alpinum*) and hundreds of medicinal and ornamental plants (*Rhododenderon, Gentiana* and *Anemone* species) (Grabherr 2009). Many of these endemic plants, however, face with the potential of disappearance, particularly in lower situated mountains (Grabherr 2009).

Although it can be seen that Austria has already showed several signs of its sensitivity to climate change and it is likely to be affected even more in various aspects of life in the recent future, no National Adaptation Strategy presently exists, and even though adaptation measures have started to be worked out, they are not fully developed yet (CIRCLE 2008). In order to avoid further adverse outcomes of such a highly altered environment it would be essential to have a more pronounced focus on climate research and its possible adaptation strategies and regulations. As Parry et al. (2008) indicate even in the implausible case of 80% of emission cutback, damages will be significant and much more adaptation efforts are necessary to hinder even more harms.

2.6. General overview of the alpine vegetation and its significance

In the Alps, mean air temperature decreases regularly with higher elevation with a rate of 0.558 – 0.65°C per 100 m, which largely determines vegetation zonations (Gottfried et al. 1999; Körner 1999). The mainly temperature and the directly linked weather factors defined belts (colline, montane, subalpine, alpine, nival) are characterized by the dominant vegetation and generally have an average extension of 700 m. The exact location and area of the belts, however, vary depending on the regional climate (Theurillat and Guisan 2001). The geographical ranges of species, especially in higher altitudes of the alpine zone, therefore indicate a strong correlation between temperature and vegetation (Huntley et al. 1995; Körner 1999; Theurillat and Guisan 2001).

As Beniston (2003) argues, mountain areas are unique regions for climate change detection. Macroclimate changes so rapidly with the elevation gradient so that zonal vegetation distribution shows signs of rich biodiversity within a given unit with numerous different transitional zones (ecotones) (Beniston 2003; Dullinger et al. 2004; Wallentin et al. 2008). Alpine regions contain highly specialized communities that are defined mainly by temperature making them predominantly exposed to climate change (Beniston 2003). In addition, the ecosystem of high altitudes is often endemic and particularly vulnerable since they are limited to specific habitats. Therefore, these areas are considered as biodiversity hotspots or islands. Alpine and nival species are unique from another perspective, as well. In contrast to lowland communities, which are not determined by elevation and thus lack of area, they cannot spread and migrate endlessly due to limited space (Beniston 2003). The research of mountain regions shows additional importance in global warming studies since, compared to other areas, here the level of human impacts is lower allowing to link modifications directly to climate change rather than to human activities (Beniston 2003; Pauli et al. 2003; Holzinger et al. 2008). In addition, high altitudes are the only terrestrial biogeographic regions, which are globally distributed in each continent, therefore providing opportunities for world-wide research data collection and comparison (Bayfield et al. 2005).

2.7. The response of alpine vegetation to climate change

The existing paradigm of the upward shift of the vegetation is that plant species migrate towards higher altitudes to meet their usual climate conditions (Beniston 2003). Hence, as temperature has increased with 1-2^{o}C since the 1980’s (Haeberli and Beniston 1998; Aerts et al. 2006), and it is expected to rise by 2.1-5^{o}C in the next 100 years (Beniston 2003; Huelber et al. 2006), this phenomenon should be continuous and possible to observe. As a result, to detect and map the upward shift of the vegetation and its long term dynamics, numerous studies (Grabherr et al 1994; Pauli et al. 1996; 1999; 2001; 2003; 2007; Gottfried et al. 1998; 1999; 2002; Dullinger et al. 2004; Erschbamer et al. 2009; Huelber et al. 2006; Gehrig-Fasel 2007; Parolo and Rossi 2008; Schröb et al. 2009) have been carried out with various outcomes. Although all of the above mentioned studies have observed alterations in location, abundance and species richness in some forms, Dullinger et al. (2003) point out that several other researchers have found irrelevant alterations of the vegetation when comparing to previous states. Theurillat and Guisan (2001), for instance, show that instead of migration, adaptation is expected to occur with 1-2^{o}C increase, which implies hardly any modifications in the recent condition of the flora. On the other hand, if the more distinct 3.3^{o}C temperature elevation takes place significant migration and extinction can arise.

2.8. Upward migration, species richness, species composition

2.8.1. Shifting of the tree line

The upward movement of alpine tree line, which is considered as an ecotone (a temporary zone between two major belts where enhanced changes occur due to its sensitivity to any alterations), can be a suitable index of climate change since it is the main control in its formation (Beniston 2003; Holzinger et al. 2008; Wallentin et al. 2008). Wallentin et al. (2008) present a research in the Austrian Central Alps, which reveals a 100-150 m upward movement since the mid 1800's mostly attributed to climate change. However, they acknowledge that the influence of land use, topographic and endogenous factors in the creation of the position of the tree line cannot be neglected.

Similarly, Gehrig-Fasel et al. (2007) point out that although the major change in the tree line position is mainly due to land use change, climate change on the longer run will seriously affect the location of the ecotone if temperature continues to rise, potentially inducing 200 m rise of the tree line. Nevertheless, they also argue that other factors, for instance, herbivores and topography should also be taken into account.

Dirnböck et al. (2003) also underline that the 2^{o}C minimum temperature increase in the 20th century did have an effect of subalpine tree species, which responded with the invasion of upper zones and with higher growth rates.

However, there are also scientific results exhibiting overall inertia in tree line dynamics (Hattenschwiler and Körner 1995; Körner 1999). Theurillat et al. (1998) show that historic records indicate low probability of rapid and unlimited upward movements, firstly, because species tend to tolerate 1-2^{o}C and secondly, because even in warmer historic climates there were upper limits of tree migration due to additional incommodities (frost, wind, lack of soil). They also underline the permanency of the warmer climate by adding:

> „For the tree line to expand upslope, even where it has been artificially lowered by man, it would be necessary for a significantly warmer climate to last for at least 100 years."

All in all, studies (Dirnböck et al. 2003; Dullinger et al. 2003; 2004; Grabherr 2009; Theurillat and Guisan 2001) suggest that if climate warming keeps on accelerating at such an alarming rate and exceeds the 1-2^{o}C mean temperature increase, tree species will adjust to the new conditions by migrating to higher elevations.

2.8.2. The alpine-nival ecotone

According to Holzinger et al. (2008), habitats of high elevation, especially the alpine-nival ecotones, are governed largely by abiotic factors, such as temperature and snow, therefore, any variations of them can eventuate serious alterations of existing communities. This alteration has already occurred showing a rise in species richness with 3 species per decade in the past 120 years, which is most probably directly or indirectly linked to climate change. However, the trends of the increase in species richness vary depending on the area, which suggests additional influencing elements e.g. bedrock, topography, so-called migration corridors and migration potential.

Pauli et al. (1996; 1999; 2001; 2003; 2007) demonstrate that climate change patterns are the fundamental modifier of vegetation ranges that affect both species richness and composition. In their studies (2003; 2007), they show a 0 and 4 meter per decade upward shift and in addition to it, a decline of nival vegetation on high summits. In contrast, increased alpine and subnival species' abundance was observed to reach site-specifically 70% or 100% boost in coverage. Besides, 10% augmentation in species richness was found in the period of 1994-2004 on one of the high summits of the Austrian Alps. All of these alterations imply that species richness, composition and abundance are and will be altered essentially due to climate change triggering potential extinction risks of those, which cannot migrate or adapt to the newer circumstances. On the other hand, drawing on Holzinger et al. (2008), they also present the importance of topographical gradient with an emphasis on the rate of disturbances and corridors, exemplifying that upward migration of mostly grass species occurred in more stable soil conditions, whereas on highly disturbed scree and steep areas, they cannot establish themselves at such a high level.

Watkiss et al. (2004) exhibit that in 21 out of 31 mountain summits, species richness increased, which is evidently a result of climate change that could cause the decline of more restricted and sensitive mountain species.

Parolo and Rossi (2008) also indicate that plant species richness and composition have changed and showed an upward shifting in the higher regions above 2000 m due to temperature warming. The fast migrants can reach more than 58 m/decade upward movements on the slopes demonstrating that the temperature is warm enough to facilitate them. Furthermore, due to more adequate conditions, invaders can establish themselves more successfully.

Erschbamer et al. (2009) and Grabherr et al. (1994) point to a similar tendency but the latter attribute a lower rate to the movement, only 4 m/decade in the Swiss National Park. It is also displayed in their paper that many taxa, which are limited to higher altitude, have been lost or potentially vulnerable to any changes of temperature and snow cover.

2.8.3. Snowbed communities

Huelber et al. (2006) reveal that the increased amount of GHG triggered by global warming does and will significantly shape ecosystems, especially those which are more sensitive to temperature amplification. Snowbed communities are among those, which are severely affected by this global process since snow cover, the major factor of their habitats, is notably reduced. This has rigorous effect on the functional traits of the plants including reproduction, flowering and budding. Further climate change will have double impacts on these plants, namely time span of reproduction will increase as well as temperature sensitivity, which might drive these species to decline or in the case of a harsh warming, to extinction

Schöb et al. (2009) reach a similar conclusion quantifying that species richness of the surveyed snowbed communities decreased by 50% besides the reduction of their relative coverage due to air and soil temperature warming. The study specifies that snowbed communities will probably suffer an overall shrinkage and their habitat will presumably be dominated by grassland species.

2.9. Additional drivers of vegetation distribution

2.9.1. Biological factors

Conversely, these changes might not be attributed evidently to climate changes since additional biological and physical factors also determine plant ranges, even if climate is considered as the major aspect (Beniston 2003; Pauli et al. 2003; 2007; Holzinger et al. 2008). For instance, Beniston (2003) suggests that in terms of biological factors, adaptations, invasions through species inter-competition and succession ability are the major controls in vegetation dynamics. Wallentin et al. (2008) add that production of seeds, seeds dispersal kernels and seedling competition are also determent among biological factors. This statement is completed with the findings of Dullinger et al. (2004) which emphasize the importance of recruitment and growth rate. Nonetheless, they also state that traits are species-specific and are dependent on the certain plant as well as the surrounding type of the vegetation. On the other hand, Holzinger et al. (2008) reveal that the key aspect in successful upward migration might be predominantly influenced by migration behaviors, which are independent on functional traits with the exception of dispersal mode, as, in general, most of the alpine species are wind transported. Kikvidze et al. (2005) point out that biological factors might be the results of climate change or the effect of the climate, thus making it complicated to differentiate them from the main influencers. However, biotic drivers, although extremely important, are more significant below the nival-alpine zone, given that above, mainly climatic patterns determine the distribution (Pauli et al. 1999; 2003).

2.9.2. Physical factors

Apart from biological drivers, physical factors also control vegetation patterns. Holzinger et al. (2008) suggest that bedrock has an a priori effect on habitats and vegetation, although

Pauli et al. (1999) indicate that vascular plant patterns on different bedrock conditions do not show relevant alterations at high elevation. However, they add that topographic elements of different bedrock areas might differ, which can induce varying vegetation distribution. Consequently, topography, the stability of the soil and the disturbance level can be one of the major abiotic drivers in the alpine and nival zone and to a smaller extent in the tree line ecotone (Grabherr et al. 1994; Pauli et al. 1996; 1999; 2001; 2003; 2007; Wallentin et al. 2008).

2.9.3. Land use change

In the lower altitudes, historic land use change can control tree line and alpine grassland development to the extent that it considerably disturbs the climate change created upward pattern. Thus, reforestation and tree line development might happen as a consequence of abandoned pastures (Nagy 2006; Gehrig-Fasel et al. 2007; Wallentin et al. 2008).

2.10. Modeling future vegetation occurrence

Taking into consideration most of the major factors, some models were constructed to assess the probable vegetation responses to climate change, and by that the determination of the location and extension of the future vegetation belts of the Alps. Even though these models are manifested in relatively few studies, each of them emphasizes the key role of the temperature factor among the other drivers.

Dullinger et al. (2003; 2004) evaluate the range of *Pinus mugo,* a dominant tree line species, and model its upslope movement based on various future climate scenarios. The models are mainly founded on the biological trait of the species including recruitment and mortality in addition to topography and temperature. They project an increase of the recent 10% distribution to reach 24-59% expansion depending on the level of the temperature growth. They indicate climate warming as the drive of the upward shift, which is however complemented with biological factors for instance, competition and dispersal rate.

The model of Dirnböck et al. (2003) takes into account predominantly physical variants (e.g. temperature, topography, wetness index, monthly solar radiation, snow cover duration, time since pasture abandonment). It shows, however, similar results demonstrating a distinctive pattern in non-forested area reduction under different climate scenarios, with the most significant change occurring obviously under the most marked temperature increase of 3.3^{o}C. The pronounced spread of *Pinus mugo* is also stressed here as this species is most likely to invade the largest alpine grasslands.

The constructive elements of Gottfried et al.'s (1999) model, where primarily the nival vegetation belts are examined, fundamentally rely on topography and temperature anomalies equally to the previous models. They observe the reduction and possible extinction of some alpine species (*Ranunculus glacialis, Androsace alpine, Saxifraga spp.*) mainly due to the invasion of pioneer grasses.

Essentially, all of the models are based on the extrapolation of historic temperature records of the nearby meteorological stations, remote sensing data (e.g. Digital Elevation Model - DEM, satellite and aerial images), biological factors and field observations, which, with the exception of biological factors, also provide the bases for the model of this study.

2.11. Discipline gap

This research field is quite new with the probably first relevant literature by Grabherr (1994), who studied the upward shift of the alpine-nival ecotone. Since then, there have been several studies dealing with the vegetation of the Alps and its responses to temperature increase, although the number of research about species' long term observations are still relatively low (Theurillat and Guisan 2001). Rather than elaborating on the overall effect of the alpine flora, most of the existing studies focus on specific segments of the vegetation, e.g. tree line shift, nival species and snowbed communities. Also, only limited number of studies (Gottfried et al. 1999; Dirnböck et al. 2003; Dullinger et al. 2003; 2004) attempt to conduct modeling and future predictions regarding vegetation belts. Furthermore, they reveal site-specific tendencies centering particular species (*Pinus mugo*) or vegetation belts. Finally, none of the climate change-vegetation interactions and modeling studies are conducted in the Karwendel region. Therefore, this study aims to fill this research gap by examining this specific area to provide an overall picture of the long-term vegetation dynamics and to create a future outlook.

2.12. The significance of the research - the potential effects of vegetation alteration due to climate change

Mountain ecosystems are particularly essential since they are often referred to as so-called islands in terms of habitat and species refugia, which due to climate change, might be altered very soon (Beniston 2003). Those approximately 800 vascular plant species, including about 300 endemic species, are particularly threatened that live in the alpine and nival zones above the tree line (Grabherr 2009). These species often have very narrow niches that make them particularly vulnerable to any modifications in the environment. However, future climate scenarios display a significant rise in temperature that will presumably alter the habitats of these plant species causing the disappearance of communities or even entire species (Grabherr 2009). The mountain flora of the less elevated mountain ranges is especially endangered because of the limited space (Grabherr 2009). Therefore, it is essential to monitor alpine vegetation dynamics, to predict future distribution, to identify key endangered and invasive species as well as potential refugia areas, and to work out conservation plans accordingly. Otherwise the valuable biodiversity of the Alps may diminish considerably with the loss of numerous species that have traditional and ethnobotanical relevance (Grabherr 2009). Furthermore, the extinction of some species and the alteration of the vegetation may modify the function of ecosystem services (e.g. mitigation of calamities, moderation of weather extremes, soil stabilization, recreation, genetic variety) (Daily et al. 1997; Sarukhán and Whyte 2005).

2.13. Conclusion

The effects of climate change on the Alps are evident impacting many aspects of life including the ecosystem. Climate change and its future scenarios indeed shape vegetation distribution of the Alps. As a response to climate change, various vegetation reactions are expected e.g. adaptation, migration and extinction in most of the belts of the alpine regions depending on the additional physical and biological factors and the rate of the temperature rise. Accordingly, it is vital to observe potential alterations and predict future patterns in order to establish appropriate adaptation and mitigation strategies in species conservation. The importance of future modeling is irrefutable since it can indicate the prospective spread of the flora as well as the potential rate of the alterations in the plant zones designating those species, which might be the most vulnerable to any sorts of changes in the environment.

3. Methodology

3.1. Overall research design

The main aim of the research is to map vegetation changes due to climate change and to determine dynamic modifications of the flora at a given location in the Alps. The research design was constructed in a way to attempt to gain a better and more complex understanding of the local vegetation and some of the main drivers of its distribution, e.g. climate and topography, in order to construct a model of future alteration in the flora in the Karwendel Alps. As a result, the methodology includes several types of information (both collected data and secondary sources).

The research plan includes:

- the collection and procession of long term temperature data (mean annual and minimum values) of four meteorological stations with the aim to analyze any change of the regional climate
- macro- and microtopographical slope angle analysis and calculation based on field data and remote sensing information
- assessing remote sensing data from 1946 and 2005 (aerial image and orthophoto) to determine the past and recent location of the tree line, and thus to detect temporal alterations
- reviewing vegetation descriptive historic records from the beginning of the last century to explore alterations of species' existence and communities
- data gathering of the plant species and micro topographical slope angle on the field concerning species richness and coverage

- a model construction to predict future vegetation distribution based on the previous trends and two different climate scenarios

Based on the achieved information, trends will be described and applied in the understanding of historic, recent and future phenomenon.

3.2. Methodology

3.2.1. Site selection

Firstly, to construct the future vegetation model of a certain location, recent and historic data of particular aspects of this location were needed. In order to aid the possibly best data collection, the site was chosen to fulfill certain criteria. Since the aim is to map the vegetation of the upper zones and its relation to climate change, those data were needed, which could indicate these factors.

The site of Hafelekar (2334 m), Nordkette, Karwendel Alps, Calcareous Alps in Tyrol is situated next to Seegrube, which possesses a meteorological station, although only since 1993. However, in the proximity two other mountain stations can be located in Zugspitze and in Patscherkofel in addition to the station in Innsbruck, which data can provide long term tendencies. Furthermore, the site has been monitored by remote sensing applications, including aerial photographs of the area, which enable to pinpoint the position of the timberline and its temporal alterations. Recent and historic data of the site's upper zone vegetation also exist, which facilitate comparison of the alpine-nival vegetation's changes in occurrence and plant assemblages.

The site of the Hafelekar, Nordkette (figure 1) is significant for other reasons, too. The selected area on the mountainside of Hafelekarspitze (2334m) is under protection since 1989

(Gartner 2000) and considered as a Natura 2000 site of community importance (Habitat Directive) and a landscape protected area (Tiris 2009). The site has a particular relevance in the region since the best quality drinking water of Innsbruck is derived from this area of the Karwendel Alps (Gartner 2000).

Figure 1. The 1:50 000 topographic map of the Hafelekar, Nordkette with the transects' lines indicated in red (Land Tirol).

3.2.2. Data collection on the field

Field data collection of the occurring vegetation is necessary in order to compare historic data and recent stages to recognize alterations in the plant communities of the area. Collection of the data takes place at higher elevation starting from the tree line (~1700-1900 m) to the upper summits to map the more sensitive ecotones in terms of climate change (Beniston 2003; Holzinger et al. 2008). Taking into account that mountains here have rather long ridges and chains, it is difficult to find a regular shaped mountain with ordinary patterns of vegetation on each side. Hence, all of the selected transects are on the same side of the mountain since cardinal points might not be the major influencing aspects to consider (Körner 1999). On the other hand, the transects are attempted to be located on different slope categories as well as on different geomorphological and vegetation featured areas in order to map local differences.

At the site, the tracks of 3 linear transects are selected to map thoroughly the upper area, from around 1700 m to the top, around 2200 m, which allows to establish general trends as well as to identify irregular cases of the mountain side (e.g. effects of topography, scree and snowbed communities). As information is required about the tree line and the above plant communities, the starting point of the transects are 50-200 m below the local tree line in order to warrant the inventory of the forest species, and to ensure that the survey starts at the same elevation level, which includes the subtreeline forest irrespectively of the fluctuation of the timberline. The lowest situated points, quadrates 1, are established based on the remote sensing maps and the topography of the area with the whole track of the transects. The exact location of the transects are decided to be approximately 150-200 m far from each other on the base point. The locations can be seen in figure 2.

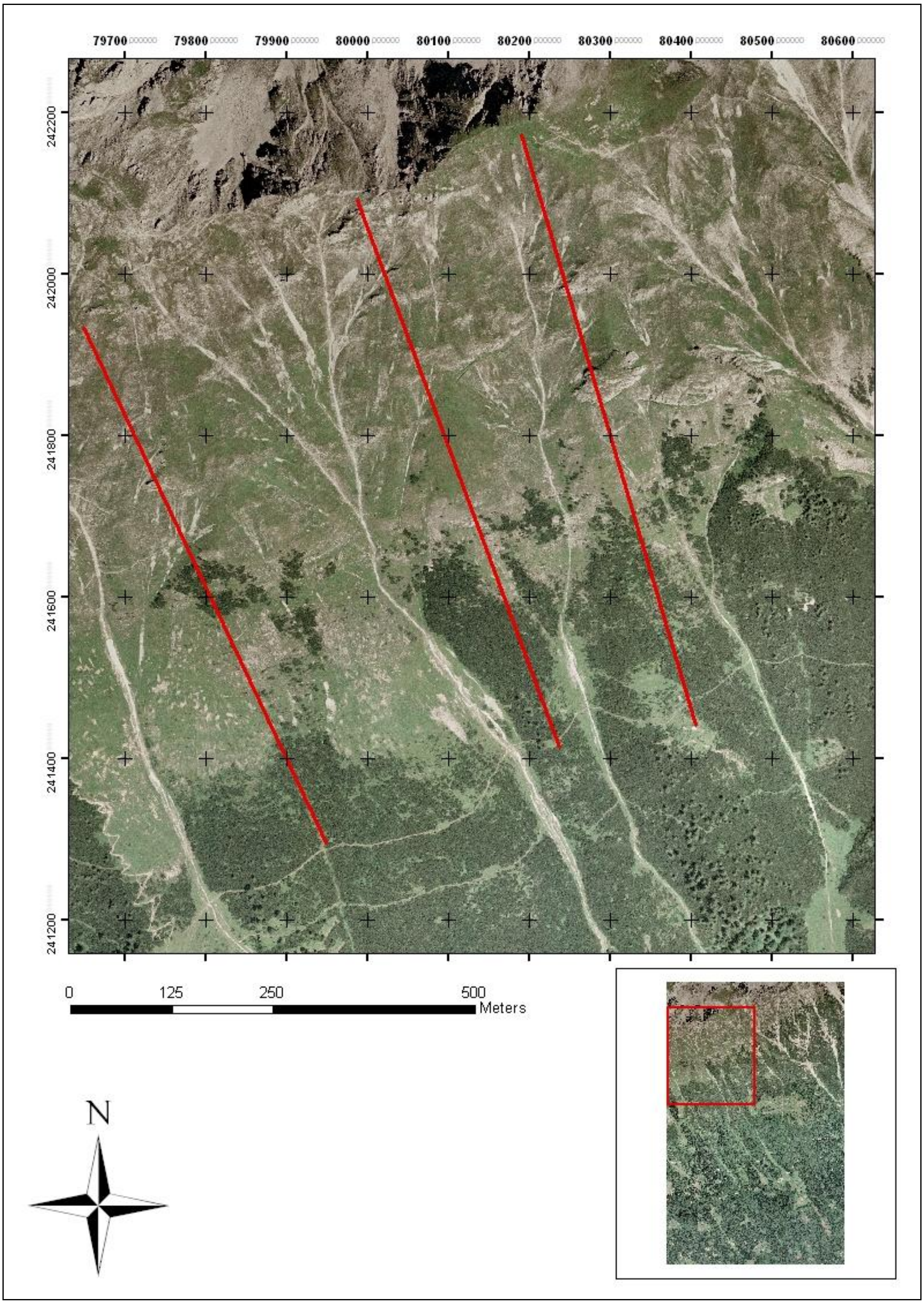

Figure 2. The location of the three transects in the Nordkette. Quadrates 1 are the starting points, situated in the lowest altitude, while the last quadrates in the proximity of the peaks. The numbers on the frame indicate the coordinates in MGI system (Land Tirol).

The tracks are designated as straight lines. The coordinates and the exact elevation are measured by a GPS. From the lowest located starting points, with the help of a 1x1 m quadrate, vegetation characteristics are determined including vegetation coverage (%), micro slope gradient (estimated value), species richness and species abundance at each 50 m to obtain a general zonation tendency. However, some of the 50 m points could not be studied directly due to slope steepness. In this case the next possible point was taken. Also, at the upper regions vertical cliffs and slope movements occurred which made it complicated to reach certain locations. Therefore, some of the peak sites were evaluated by photographs.

3.2.3. Secondary data

Temperature data

At the site, in the Seegrube, Nordkette a meteorological station has been operating since 1993. Raw temperature data (provided by Lawinenwarndienst Tirol, Innsbruck) have been measured every 10 minutes daily from September till May. Since 16 years of temperature data (1993-2009) do not display long term tendencies, the records of two additional and nearby mountain stations were required in order to obtain historic temperature measurements. There is an additional mountain station in 5 km (Patscherkofel 2246 m), and another one in 35 km (Zugspitze 2962 m), which have worked for longer periods and which data could be used to calibrate average values for the site as it was done in similar vegetation projecting and modeling studies (Dullinger et al. 2003; Dirnböck et al. 2003). The temperature data of Patscherkofel were gained through the Austrian Meteorological and Geodynamical Centre (ZAMG). Because they only provide mean values for certain periods (1961-1990, 1971-2000 and from 1995 annually) these records are complemented with literature data (Pitschmann et al. 1970). Daily temperature records (the highest and lowest measured) of Zugspitze station from 1900-1999 is available through the German Meteorological Service (DWD). In order to calculate historic average temperature of the site more precisely, the temperature data of Innsbruck from 1900-2000 were also utilized (based on a ZAMG's publication Auer et al. 2008).

Remote sensing data

According to Wallentin et al. (2008), tree line modification can be clearly visible on aerial photographs on a long-term base. These types of remote sensing images are also applied here in order to determine the temporal shifting, if any, of the timber line. Black and white aerial photo of the area from 1946 was obtained from the local municipality's remote sensing section (Land Tirol, tiris - Tiroler Raumsinformationssystem – Spatial Information Sytem Tyrol). This was then calibrated into an orthophoto by Globalmapper to allow calculation on the image. Also, an orthophoto of the same area from 2005 was gained via Tyrol municipality.

The upward shift of the timberline is not always linear and also patchiness can occur, which can be attributed to certain changes in the geomorphology (Wallentin et al. 2008). Therefore, it is important to take macrotopography into consideration as one of the influencing drivers of tree line migration, which can be measured by digital elevation model (DEM). This allows for a better understanding of tree line dynamics in correlation with altitude. As a result, a DEM of the area was created based on the contour map (Land Tirol) and the orthophoto of the region.

Historic data and recent descriptions

Information from previous research of the Karwendel Alps' flora is very valuable because communities and species cannot be precisely detected by remote sensing tools. Therefore, to gain data about the then occurring species and the modification of the vegetation, historic records of the site were used. The documentation of the vegetation of Hafelekarspitze and the close environment were mostly elaborated in the work of Pitschmann et al. (1970) whereas a vertical transect from the mountaintop till the valley was conducted mapping the vegetation types and their boundaries in respect of the altitude. Also, Grabner (2000) in her work of the alpine and subalpine vegetation reveals detailed historic records from Rübel (1911), Lüdi (1921) and Jenny-Lips (1933), as well as recent data of the exact site of Hafelekar.

3.2.4. Data procession

Fieldwork data

Three Excel sheets were created for each transect to list all of the detected species throughout the transect and the occurring species of particular sites. The growing plant species of the quadrates are represented with their coverage percentage or with an "x", if they appeared inside the quadrate but without significant abundance. Besides coverage, altitude, species richness and the local micro slope angle are indicated (Appendix 1).

Temperature data

The temperature records were also processed in Excel. From the raw data of the meteorological stations mean annual temperature values were gained, or in the case of the Seegrube station, the mean temperature of January, the coldest month (Gagen et al. 2006), was analyzed to detect the mean minimum temperature change, since annual temperature values could not be obtained (the station only operates from September till May). In order to verify that Seegrube's station and thus, the examined site does not have a very distinctive local climate pattern, the mean January temperature of Patscherkofel was also elaborated. The results were illustrated in diagrams.

Remote sensing data

The information of the aerial image and orthophoto was processed by ArcGIS to assess modifications of the tree-covered area and the shift of the tree line by measuring the total covered area of the woody plants and the distance between the historic and recent tree line's average location. The measurements were based on the various pixel values of the tree vegetated spots. The average tree line positions of the two different periods were calculated by the altitude of the tree's average distribution at the surveyed site.

A contour map of the area was also digitalized with 20 m-unit altitude lines, and a Digital Elevation Model (DEM) was constructed of the area by ArcGIS. The DEM and the tree coverage maps were merged together to explain potential relationships between the coverage and slope gradient. All maps of the study are based on maps provided by Land Tirol and produced by ArcGIS.

Historic and recent vegetation data

The species from historic records of Rübel (1911), Lüdi (1921) and Jenny-Lips (1933) (cited in Grabner 2000) were listed in habitat and altitude categories, and were placed into tables (Appendix 2) in order to allow for a comparison with the recent field and literature data. The exact altitude is particularly essential to examine where plants were then and are currently found as well as what types of communities and species are missing now, which could be found here before.

The modeling framework and future projections

The modeling framework is based on two fundamental assumptions: (1) physical factors, climate change in particular, are the dominant agents to define vegetation distribution and (2) the rate of upwards migration is consistent with that of climate change. Following Dirnböck et al. (2003) and Dullinger et al. (2003), the model is built on extrapolated temperature data (0.65^{o}C per 100 m gradient), which were derived from the records of the four (Seegrube, Patscherkofel, Zugspitze, Innsbruck) nearby stations, and which were adjusted to the different altitudes of the site. Along with this, from the images' pixel values, the two positions of the average tree line in 1946 and 2005 were calculated (for the 1946 temperature values the records of Innsbruck and Zugspitze, while for 2005 values, the data of all four stations were used), and their altitudes were attributed to the calibrated temperature values. From this the temperature variation and the average rate of the upward migration in this period could be achieved. This ratio of migration level (m)/temperature change (ΔT) provides the base of the model for the further predictions since it is presumed that from the past tendency of the tree line shift's speed and the extrapolated historic temperature records, the potential distribution ranges of the trees can be assumed. The hereby constructed projection is demonstrated by ArcGIS considering the two different climate scenarios of 1-2^{o}C and the <2^{o}C mean temperature increase by 2050 added to the 1961-1990 calibrated mean temperature values (Dullinger et al 2003; Emrich 2008). Accordingly, the probable ranges of the forested area by

2050 are determined between 1-3^{o}C threshold values with differentiated migration ratios in order to display the possible fluctuation sensitivity of the model.

Furthermore, the area and the distribution of the vegetation pattern are also evaluated in terms of the slope gradient to be combined with the tree line model in order to receive the highly invasive grassland zone probable extension, as slope gradient and the related migration corridors tend to be the main factors in the dominant grasslands' invasion to the alpine and snowbed belts (Pauli et al. 2003; 2007; Holzinger et al. 2008). This part of the model, namely the estimation of the probable expansion of the grassland by 2050, is based on two assumptions: (1) grass species also proceed upwards parallel to climate change, invading and outcompeting alpine species in the higher regions, and (2) slope angle is the additional governing factor in their distribution. Based on these presumptions, a model can be created combining the DEM and the tree line model, to designate the possible grassland areas as well as the refugia spots for the alpine and snowbed communities, which may be able to endure on connected steeper microhabitats above 2100 m.

3.3. Advantages and limitations of the research plan

3.3.1. The benefits of the methodology and the overall research

The study aims to identify historic variations, the recent stage and the future outlook of the vegetation with various methods. One of the advantages of the research is its attempt to review the complex vegetation modification of Hafelekar's upper regions in relation with climate change and other controls in contrast with other surveys, which are rather concentrated either on the tree line shift or on the alteration of the nival vegetation and snowbed communities. A further benefit of the survey is to apply and combine different techniques (analysis of temperature and remote sensing data, historic records and fieldwork documentation, modeling) in the mapping of the species' spatial and dynamic distribution. Furthermore, this paper aspires to draw general conclusions from the received information, and to generate broader implications and future projections to aid theoretical development as well as conservation in practice.

3.3.2. Limitations of the study

The scope of this research is limited to the surveyed geographic area making it difficult to conclude an overall tendency based on this study alone. Also, even if modification of the vegetation is evident in time, it may be hard to connect it directly with climate change. As the literature reveals, land use, biological factors and physical factors might be additional determining causes in addition to physical changes attributed to climate change (precipitation, reduction of snow coverage), although the direct effect of climate warming is inarguable (Beniston 2003; Dullinger et al. 2004; Gehrig-Fasel 2007; Holzinger 2008; Huelber et al. 2006; Kikvidze et al. 2005; Pauli et al. 2003).

Furthermore, the somewhat low numbers of transects and quadrates can restrict the validity of the data collected because the occurrence of the species, or the altitude, at which they were found may not represent a general pattern. Yet, the collected information is similar to the literature's descriptions about alpine species and habitats, and although certain dissimilarities can be detected, the general tendency of the field records follows the results of the cited literature.

Also, the model of the future estimates is only outlined on the ground of calibrated regional climate change, and to a smaller extent to slope gradient excluding further biological and physical factors, although the role of additional drivers, e.g. perturbation, land use and the additional biological factors, are discussed in the main findings section. Furthermore, the future outlook of the vegetation is based on the previous rate of the tree line shift, macro topography, field observation and tendencies described in the literature, which probably cannot provide a very precise and exact model due to lower resolution and non-direct measurements. Nevertheless, it might be suitable to produce general trends and rough estimates of the future distribution that can provide guidelines for conservation strategies.

4. Results

4.1. Temperature data

Seegrube meteorological station (1938 m) is located in the Nordkette, approximately 500 m far from the study site of Hafelekarspitze. It has been operating since 1993 measuring weather conditions, e.g. temperature, humidity and wind speed every 10 minutes, 24 hours from September to May. The obtained raw data were provided by the Lawinenwarndienst Tirol from which the mean temperature of the coldest month (January) was calculated in the period of 1993-2009 to obtain a tendency in minimum temperature variation as the evaluation of the mean annual temperature was not possible due to the limited data (figure 3).

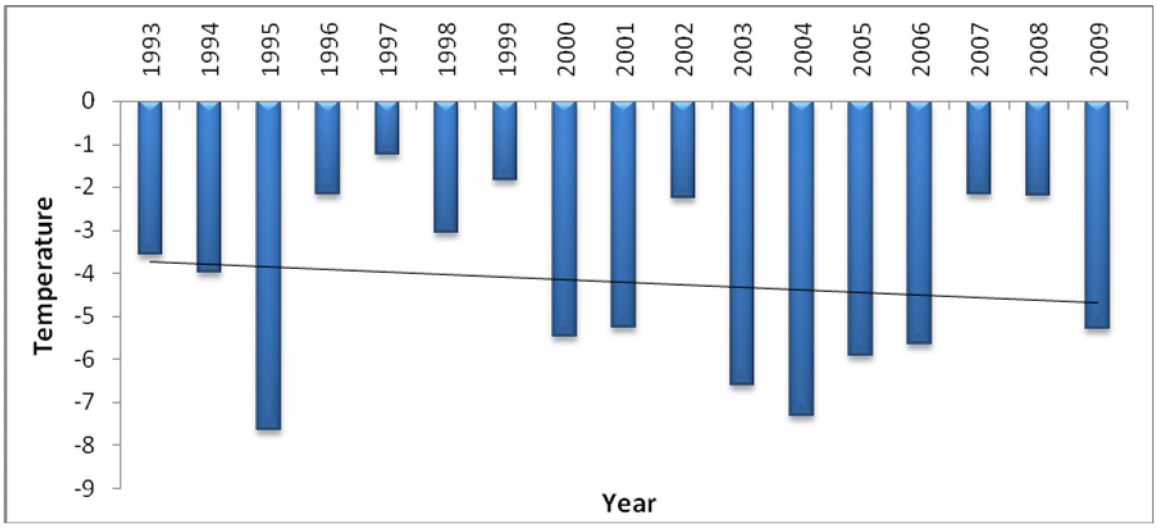

Figure 3. The mean January temperature in Seegrube, Nordkette and its trendline in 1993-2009.

The mean January temperature is -4.21^{o}C during the period of 1993-2006. Evident warming or cooling tendency cannot be observed although slight temperature decrease occurs as a result of the colder years in the mid 2000's. Furthermore, significant, several grade (2-3^{o}C) fluctuations between the years of 2002-2003 and 2006-2007 can be observed.

Patscherkofel (2246 m) temperature records were received mainly from the Austrian Meteorological and Geodynamic Centre (ZAMG 2009) and to a lesser extent from the work of Pitschmann et al. (1970), where the temperature values are measured and averaged in the periods of decades. Pitschmann et al. (1970) reveals that the mean January temperature was -6.1^{o}C, while the mean annual temperature was 1.3^{o}C in the period of 1951-1960. According to the ZAMG records, in 1961-1990 colder temperature values were measured with a -6.7^{o}C as the mean January, and 0.2^{o}C as the mean annual values. In 1971-2000, the measurements display -6.3^{o}C as the mean January, and 0.0^{o}C as the mean annual temperature. Figure 4 takes into account the temperature records of 1951-1960, 1961-1990 and the annual values from 1995 until 2007. It demonstrates the mean January temperature records with the aim to investigate whether Seegrube's tendency shows site-specific results or it is similar to Patscherkofel's records. The two datasets significantly correlate (R^2 = 0,967) indicating region-wide trends in the mean January temperature change. Figure 5 also uses the temperature records of 1951-1960, 1961-1990 and the annual values from 1995 until 2007 presenting the mean annual temperature values. However, it has to be added that exhibiting the mean temperature of the decades might distort results.

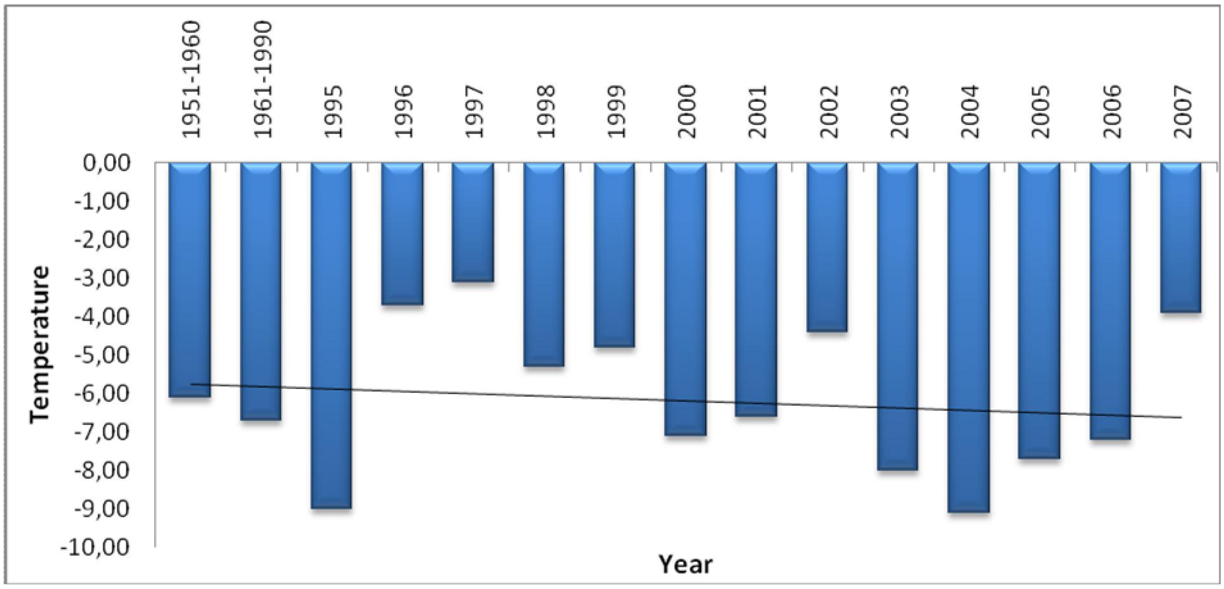

Figure 4. The mean January temperature values and their trendline in 1951-2007 from the Patscherkofel (2246 m) meteorological station.

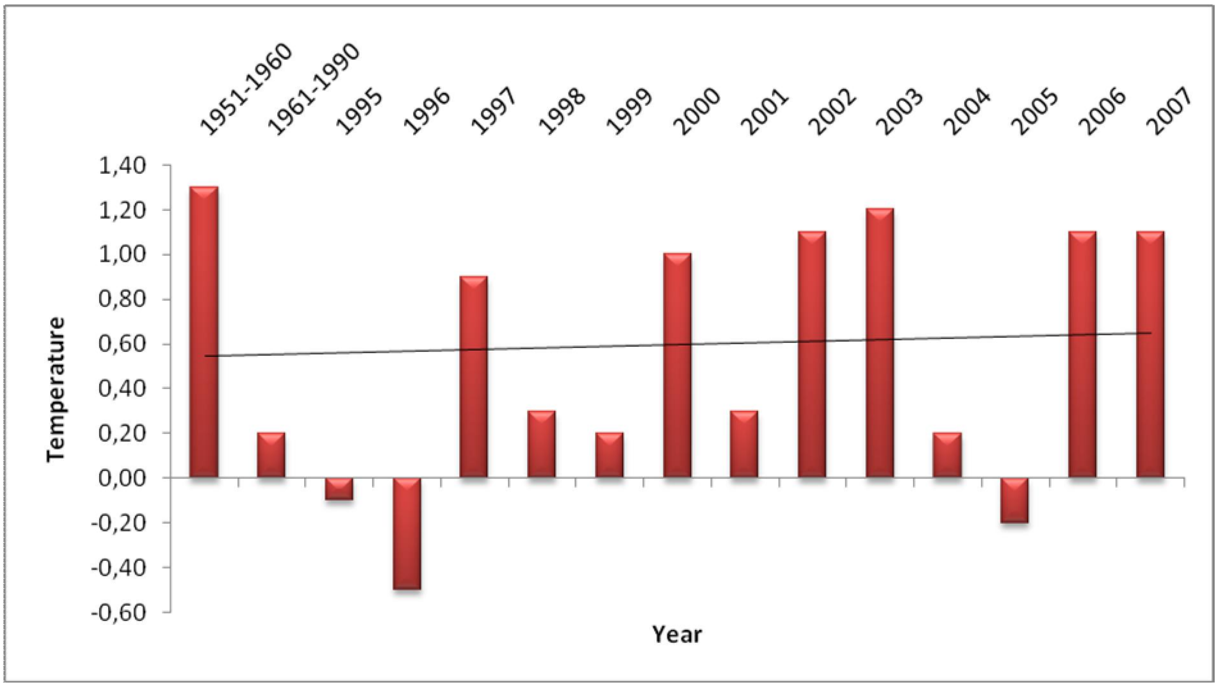

Figure 5. Mean annual temperature values 1951-2007 from the Patscherkofel (2246 m) meteorological station.

It can be seen from the charts that while the mean annual temperature indicates modest average warming of the area with an approx. +0.2°C, the general trend in January temperature implies moderate cooling. Therefore, the mean January values of Patscherkofel specify similar tendency about the colder and warmer years, corresponding to the measurements made in Seegrube's station.

The meteorological station of the Zugspitze (2962 m), operated by the German Meteorological Service (DWD), provides climatic information of the highest and lowest measured daily temperature in 1901-1999 (figure 6). Zugspitze data reveal that average air temperature increased by approx. +1°C by the end of the 20th century compared to the 1900's. Also, general 5-10 year fluctuation tendency can be noticed throughout the century as temperature gradually increases then drops again.

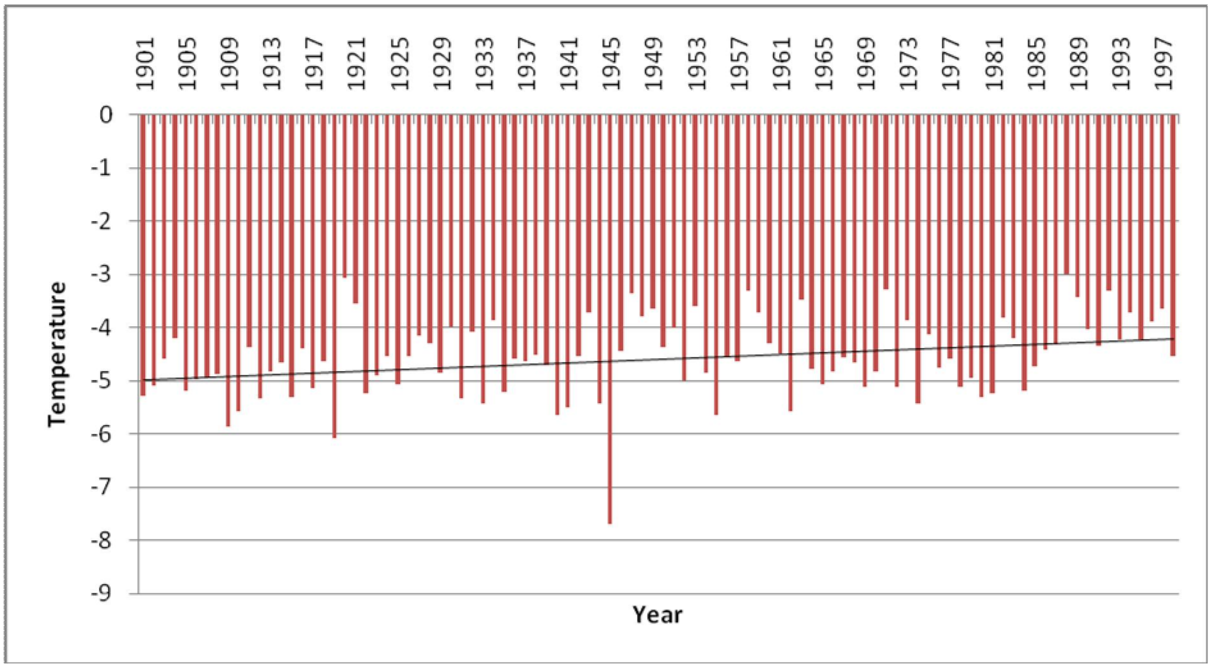

Figure 6. Mean annual temperature values and their trendline measured by Zugspitze (2962 m) meteorological station from 1901-1999.

4.4. Analysis and procession of the remote sensing data

4.4.2. Slope angle and contour lines

The contour lines map and the associated Digital Elevation Model (DEM) of the surveyed area in Hafelekar, Nordkette categorize the elevation variation, the steepness and to a smaller extent the microtopography of the mountain slopes, which are regarded as key factors in vegetation distribution of the alpine regions (Grabherr et al. 1994; Pauli et al. 1996; 1999; Wallentin et al. 2008).

The position of the contour lines (figure 7) indicates more or less a gradual elevating trend on the mountain slope with similar, approximately 20 m distances between the 20 m-height units. However, the lines widen, indicating larger area between height alterations on the geomorphological forms of smaller ridges and valleys, while they occur more frequently in the proximity of cliffs, mostly above 2100 m.

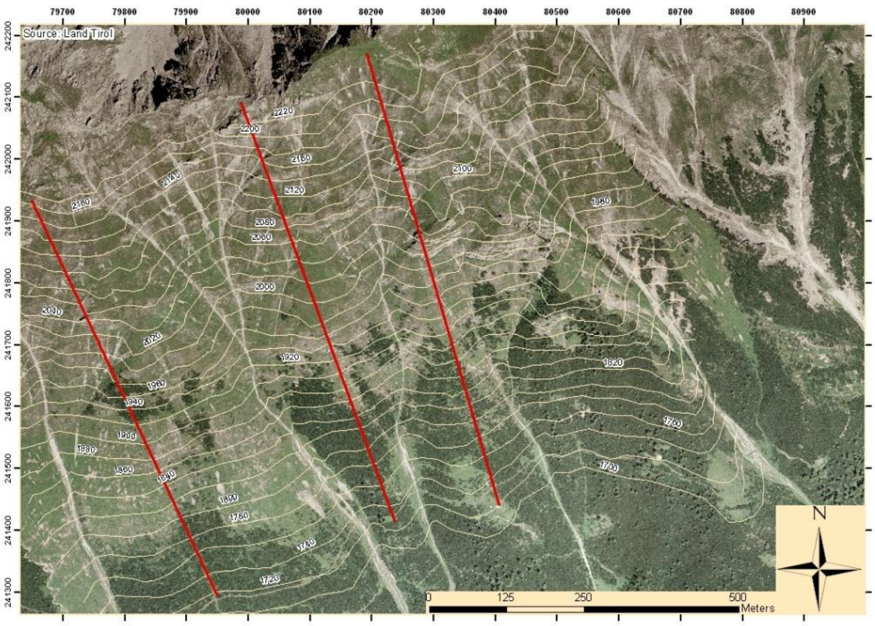

Figure 7. The contour lines of the Nordkette area of the transects with 20 m elevation units (Land Tirol).

The DEM model (figure 8) is based on the contour map (elevation alteration and distance between the height values), and classifies the various slope angles of the mountain sides. The model exhibits nine categories of slope steepness varying from 0 to 60 degrees. The minimum and maximum slope angles differ between 0 and 62.32^{o} with an average of 33^{o} of the site. Also, similarly to the elevation, slope gradient is likely to be more accentuated as elevation increases and nearby cliffs, while flatter areas, indicated by greener dots, can be detected mostly at ridge and valley locations.

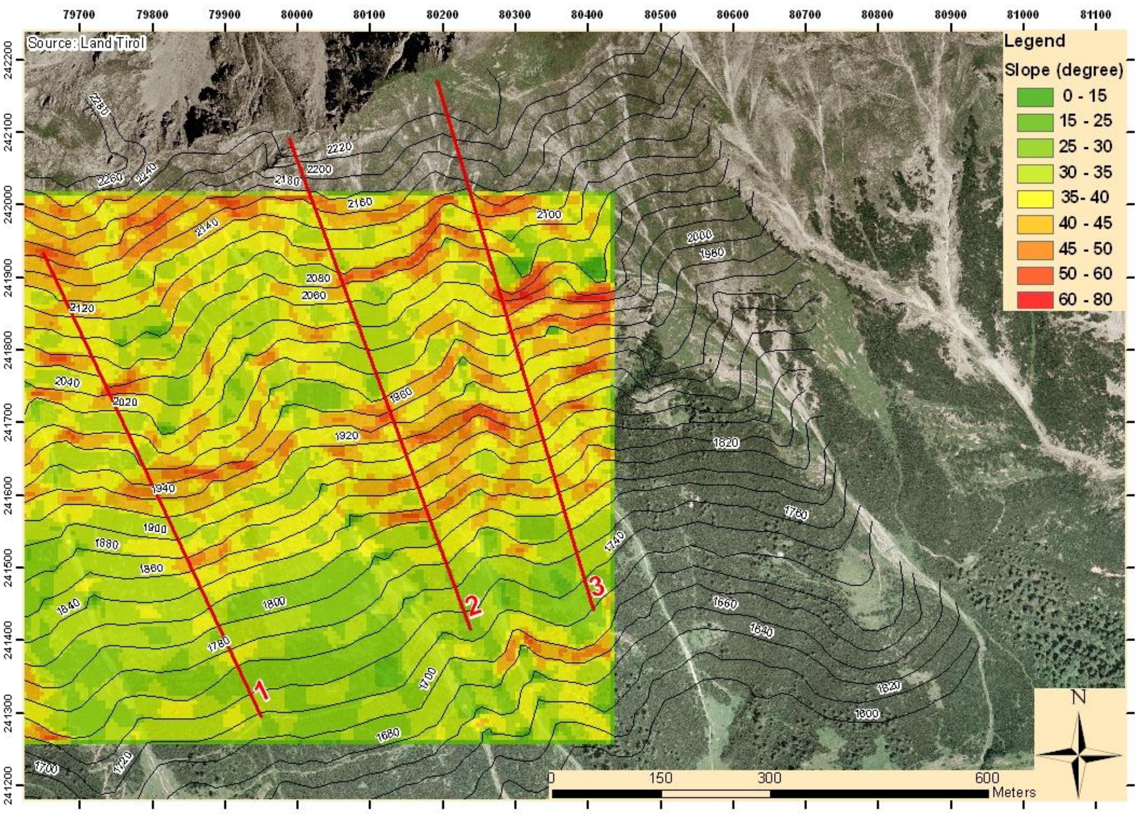

Figure 8. Slope degree categories of the Hafelekar, Nordkette in the proximity of the transects. Greener areas indicate lower level of vertical change while yellow and red areas represent 35-60o slope steepness (Land Tirol).

4.4.3. Tree line alteration between 1946 and 2005

The woody vegetation of the site in Hafelekarspitze, Nordkette are designated with green color on both the aerial photo of the site from 1946, which is one of the first record of the area (figure 9) and in the most recent orthophoto from 2005 (figure 9). They are merged into one image to allow comparison (figure 9). Due to the high resolution of the images, the measurements have m^2 accuracy, however, the conversion of the aerial image probably resulted in distortion around the edges. The blue frame signs the analyzed 617 000 m^2 large area.

The tree-covered vegetation in 1946 was 91 132 m^2 on the surveyed area, whereas the tree line was positioned in the average height of 1756 m. In the Western part of the first transect, the woody plants were situated under the 1840-1880 m contour lines with less intense occurrence, though they also persisted in smaller spots at higher positions roughly in 1920 m. The tree line in the Eastern site of transect 1 gradually descended from 1780-1800 m to 1720-1740 m with higher situated smaller bunches. The woody vegetation in the proximity of transect 2 reached 1880 m, although trees could be found more commonly in 1840-1820 m, while smaller assemblages can also be detected here at the more elevated sites. Around transect 3 the homogenous occurrence of the tree position is the lowest in 1760-1780 m with higher placed groups. At the same location, below the timber line, a larger clearance area can also be seen, which is surrounded by woody vegetation.

In 2005, the tree-covered area increased to 113 900 m^2 creating a difference of 22 737 m^2 compared to the vegetation distribution in 1946. The average timber line of the site also enhanced to 1780 m, 24 m higher than in 1946. The tree line in the proximity of transect 1 can be placed between in 1740 and 1800 m although there are patches in higher altitudes up to 1980 m. Around transect 2 woody vegetation can be found in 1900-1920 m similarly to

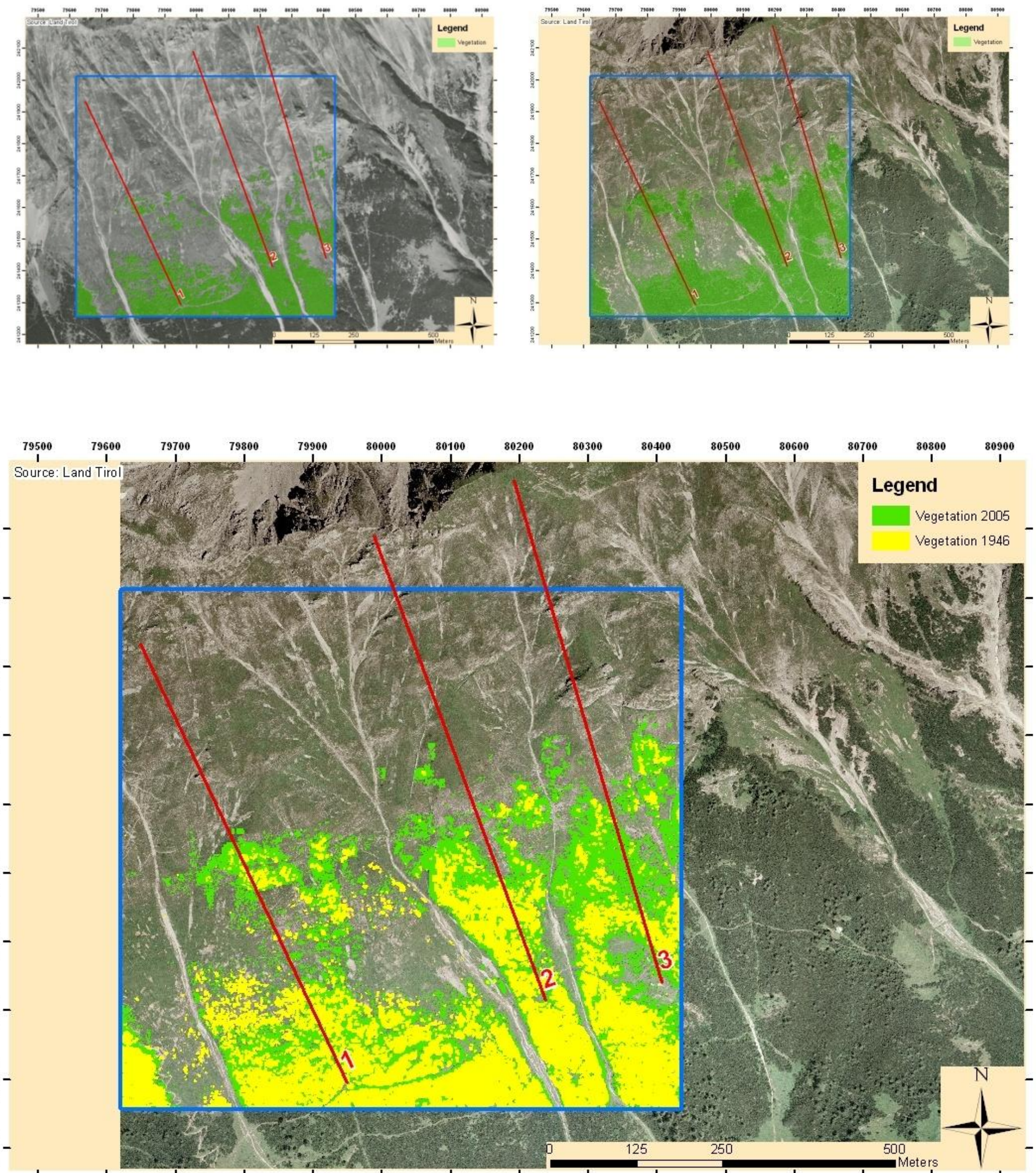

Figure 9. The 1946 aerial image and the then tree-covered area (green) in the left up corner and the 2005 orthophoto with the tree-covered area (green) in the right up corner. The larger image demonstrates the tree line and the tree covered area of the site from 1946 (yellow) and 2005 (green) (Land Tirol).

transect three. In all of the cases however, there are minor, non-covered patches under this line. These barer spots can also be discovered in the older aerial image although there they had larger extensions.

In general, an overall upward shift of the timberline can be seen as well as a denser coverage under the tree line with smaller, non-woody vegetated areas in 2005. On the other hand, a distinctive example can be specified on the Western part of transect 1, which was more occupied by trees in 1946 than it is today.

4.5. Historic records and recent descriptions

The historic records of typical species and their associations from the subalpine and alpine zones can be read in the works of Rübel (1911), Lüdi (1921) and Jenny-Lips (1933) (Grabner 2000). They classify the representative species in terms of their mountain habitats, such as tree line area, subalpine-alpine grasslands in 1900-2100 m, Seslerio-Caricetum sempervirentis above 2100 m, scree and snowbed vegetation (Appendix 2). Some of the species listed in their works were not discovered at the recent site during the fieldwork, and neither were they enlisted in other current vegetation assessments about the site (Grabner 2000). These species are designated with red color in Appendix 2.

Pitschmann et al. (1970) also examine the area exhibiting a vertical transect of Hafelekarspitze displaying the dominant vegetation in terms of its altitudinal extension. The belts with the most dominant species can be seen in table 1, where Grabner (2000)'s description of the belts, based on recent data and Pitschmann et al. (1970)'s paper are also indicated to allow comparison of both altitudinal dimensions and species occurrence.

Altitude (m)	Vegetation belts of Hafelekar, Nordkette (Pitschmann et al. 1970)	Altitude (m)	Vegetation belts of Hafelekar,Nordkette (Grabner 2000)
1050	Abieto – Fagetum with Picea (Fagus sylvatica, Pinus sylvestris)	800-1100	Picea abies
1200	Piceetum montanum (Larix decidua, Pinus sylvestris, Picea abies)	1100-1200	Pinus sylvestris
1700	Pinetum mughi (Pinus mugo)	1200-1700	Picea abies
2030	Erico – Rhododendretum hirsuti and Dryadetum (Erica carnae, Arctosstaphylos alpina, Rhododenderon hirsutum, Dryas octopetala)	1700-2050	Pinus mugo with Erica carnea, Rhododendron hirsutum (Sesleria albicans, Phyteuma orbiculare, Campanula scheuchzeri, Daphne striata.
2090	Festucetum vioalacea, Festucetum pumilae, Caricetum ferruginae, Caricetum firmae Androsacetum alpinae, Salicetum herbaceae, Polytrichetum sexangularis	2050-2100	Dwarfshrub heath (Erica carnae, Salicea, Rhododenderon hirsutum) with Dryas octopetala
		2050-2300	Seslerio-Caricetum sempervirentis (Potentilla aurea, P. erecta, Briza media, Crepis aurea and Alchemilla vulgaris, Ranunculus alpestris, Saxifraga caesia, S. oppositifolia, Pinguicula alpina, Minuartia sedoides, Chamorcis alpina).

Table 1. The vertical extension of vegetation belts and dominant species of Hafelekar, Nordkette based on Pitschmann et al. (1970) and Grabner (2000).

According to Pitschmann et al. (1970) and Grabner (2000), the most dominant species of the area are *Pinus mugo, Juniperus communis ssp. alpina, Vaccinium spp., Rhododendron hirsutum, Sorbus chamaemespilus, Erica carnae, Sesleria albicans, Carex spp., Phyteuma orbiculare, Valeria Montana, Daphne striata, Hieracium bifidum, Dryas octopetala, Ranunculus alpestris* and *Saxifraga spp.*

4.6. Transect data

4.6.2. General trends

All three transects are situated in Hafelekarspitze's Southeast mountain side, in Nordkette. The transects have their first quadrates at around 1720 m and end points at an approx. 2200 m high each crossing 700 m and containing 14-15 quadrate positions at each 50 m. Inside the quadrates coverage of the dominant vegetation, the slope angle of the area of the certain quadrate (not the average slope angle) and species number were recorded.

It can be seen from the derived data that all transects' coverage (figure 10) exhibits higher values at the initial points of the transects, however, there are some lower values both at lower and higher altitudes. The average coverage of the surveyed area is 68%, the average values of each transect' first 5 sites are 78.82%, the next 5 sites are 70%, whilst the vegetation in the last 4, or in the case of transect 1, 5 sites, cover only 53%.

Slope angle (figure 11) tends to take higher values as altitude increases, however, it can also change drastically even between neighboring sites, especially at higher elevation (figure 11). The average slope degree at the first 5 sites of each transect is 32^{o}, the next 5's slightly higher with 37^{o}, while the last 4/5's average value is 52^{o}.

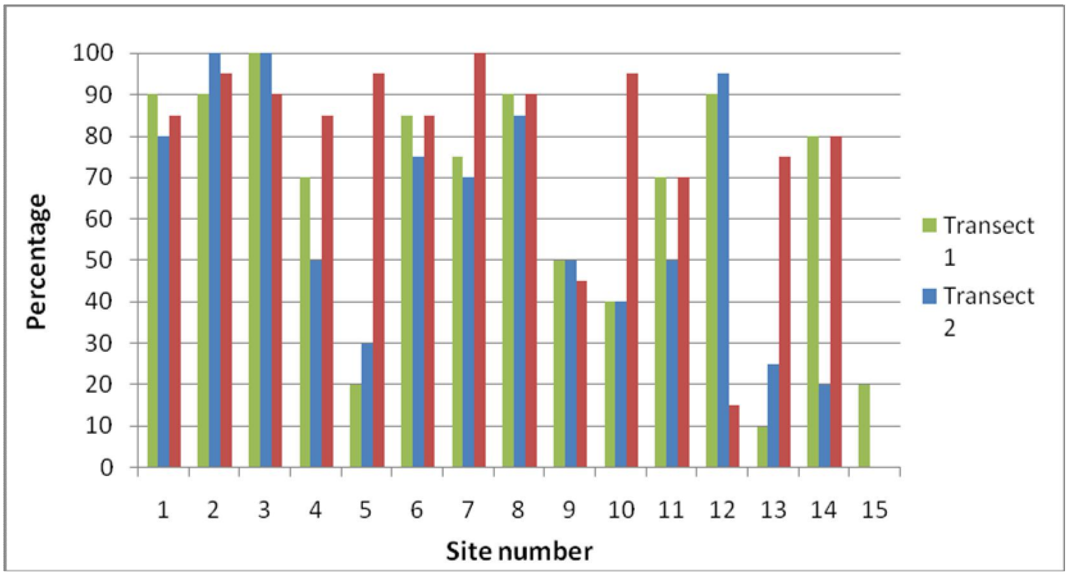

Figure 10. Coverage data of the sites of each transect in percentage.

In contrast with slope angle, species richness (figure 11) is represented with decreasing numbers with higher elevation. Whilst the first and middle sites of the transects include an average 9.5 and 10 species, the quadrates of the peak area contain only an average 6.8.

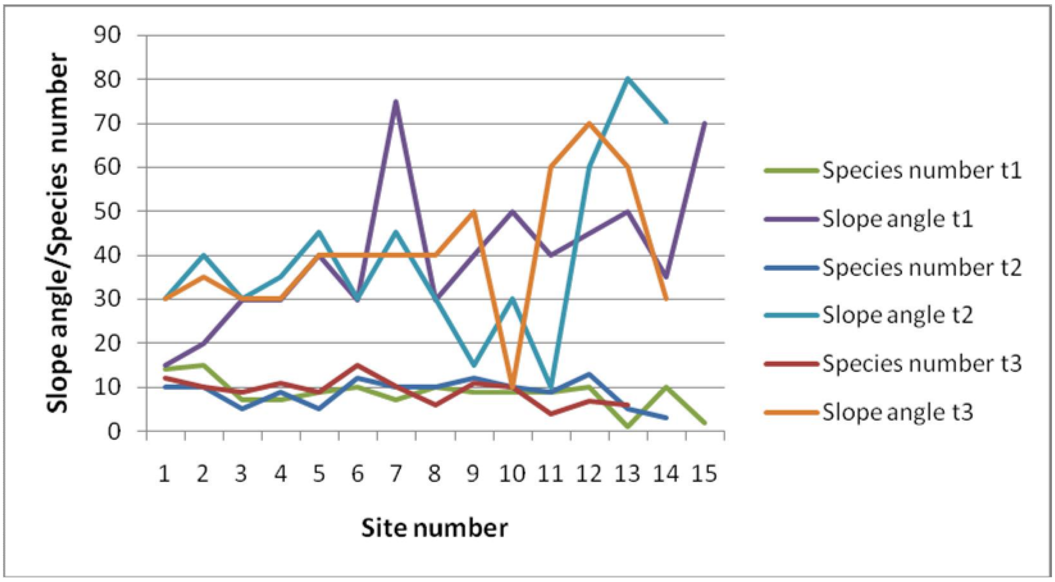

Figure 11. Slope angle in degree and species number of each site of the three transects.

In terms of species distribution, the general tendency signifies the dominant occurrence of *Pinus mugo* and associated species until 2000 m, more densely at the first section of the transects, which are normally followed by *Sesleria albicans* and *Carex sempervirensis* grass species, often complemented with *Erica carnea* associations. Above 2070 m snowbed and alpine species start to occur, mainly *Saxifraga aphylla, Salix serpillifolia, Silene acaulis, Dryas octopetala* and moss species, nevertheless, they are more common above 2100. Certain plants, such as *Sesleria albicans, Carex sempervirens, Erica carnea, Daphne striata, Gentiana spp.* and *Alchemilla alpina* are the most wide-spread and could be found in most of the altitudes. During the fieldwork altogether 106 species were identified, although many of them are not included in either of the transects' sites, since they did not occur on the surveyed plots, but in their proximity. They are listed in Appendix 1.

4.6.3. Transect 1

Transect 1 is located on the most Western part of the area covering an approximate 750 m long section through the mountain slopes of Hafelekarspitze in the Nordkette. The transect is the most extended containing 15 surveyed quadrates on the slopes. The microtopographical angles vary between 15^o and 75^o with an average of 40^o throughout the whole section, but with almost double values at higher locations compared to the first lower sites (figure 12).

The average coverage of vegetation is 65.3% with percentages between 10 and 100%. It can be observed that the coverage percentage's figure does not show very evident tendency with displaying extreme drops (figure 12). On the other hand, the distinction of the average numbers between the first and last five sites is more than 20%.

The usual species number at the sites is 8-9, even though spots with both 1 and 15 plants species can be found (figure 12). Plant species richness is also normally higher at the initial locations (10.4) compared to the upper sites (6.4) due to the more accumulated numbers of 15 species at 1725 m-1750 m high and less abundant sites with 1-2 species at 2225 m and 2293 m high. Nonetheless, it has to be mentioned that some of the elevated sites contain 10 species, while lower locations can have 7 representatives of the flora.

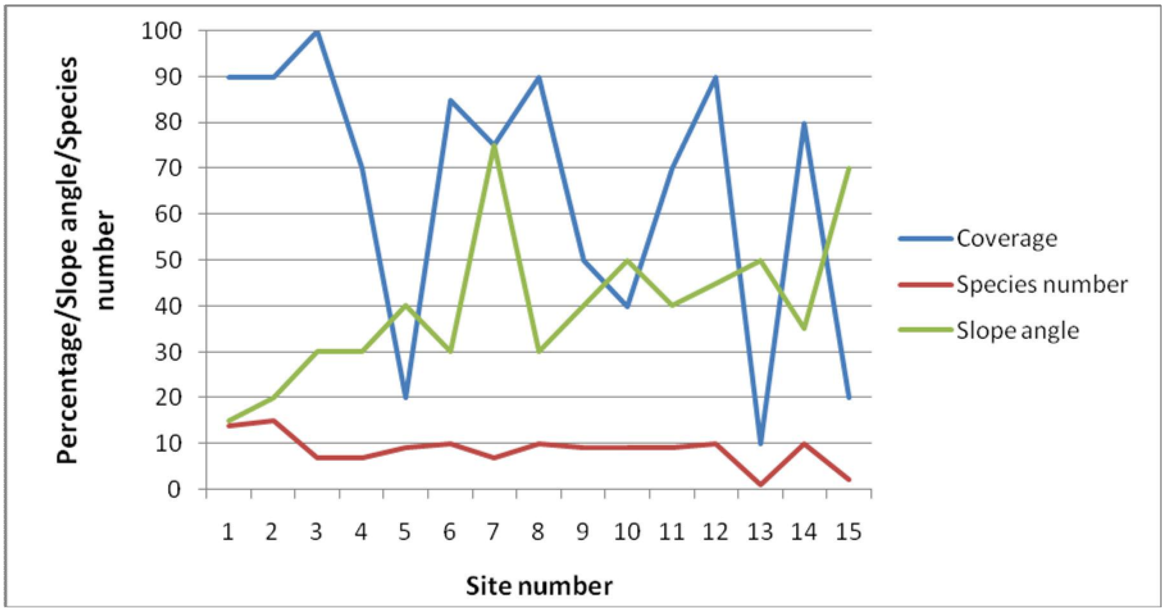

Figure 12. The characteristics of transect 1 including coverage (%), species number and slope angle of all 15 sites.

At the sites between 1725-1800 m *Pinus mugo* is the most dominant species, which occurs with *Carex firma*, *Carex sempervirens*, and *Sesleria albicans* at a more significant level and with frequent but less widespread coverage of *Alchemilla alpina*, *Erica carnea, Viola biflora*, *Juniperus communis ssp. alpina*, *Pulsatilla vernalis, Ranunculus montanum, Senecio doronicum.* At these sites, average coverage is 87.5%, species number is 10.75 and slope angle is 23.5^{o}.

Site 5 indicates a distinctive pattern with solely 20% of coverage, 40 degree slope angle but with the average number of 9 species specifying previously non-growing plants, more commonly *Carduus defloratus, Festuca rubra, Taraxacum officinale agg.* and *Galium vernum*.

The next seven sites at the altitude of 1873 m-2111 m represent universality in plant association with *Erica carnae, Sesleria albicans, Globularia cordiflora, Lotus corniculatus, Gentiana brachiphylla, Carex sempervirens* and *Alchemilla alpina* with a rare appearance of *Pinus mugo* in 1939 m. Each quadrate presents the transect's average values of all categories with the exception of site 7, which has the steepest microtopographical slope with 75^{o}and only 7 species.

The last three sites above 2200 m have a different flora world, which mainly consists of *Silene acaulis, Saxifraga aphylla, Silene acaulis* and moss species with *Carex firma, Daphne striata* and *Homogyne alpina*.

4.6.4. Transect 2

Transect 2 goes through an approximate 700 m area with 14 sites, which are positioned between 1737 m and 2214 m. The transect's average microtopographical slope angle is 39.28^o with 10^o lowest and 80^o highest measurements. This transect shows similar tendency with less dissimilar quadrate's data at the first part of the sites with an average 30^o slope gradient, whereas at the last five sites this value reaches 55 ^{o}, although with flatter spots at the higher regions (figure 13).

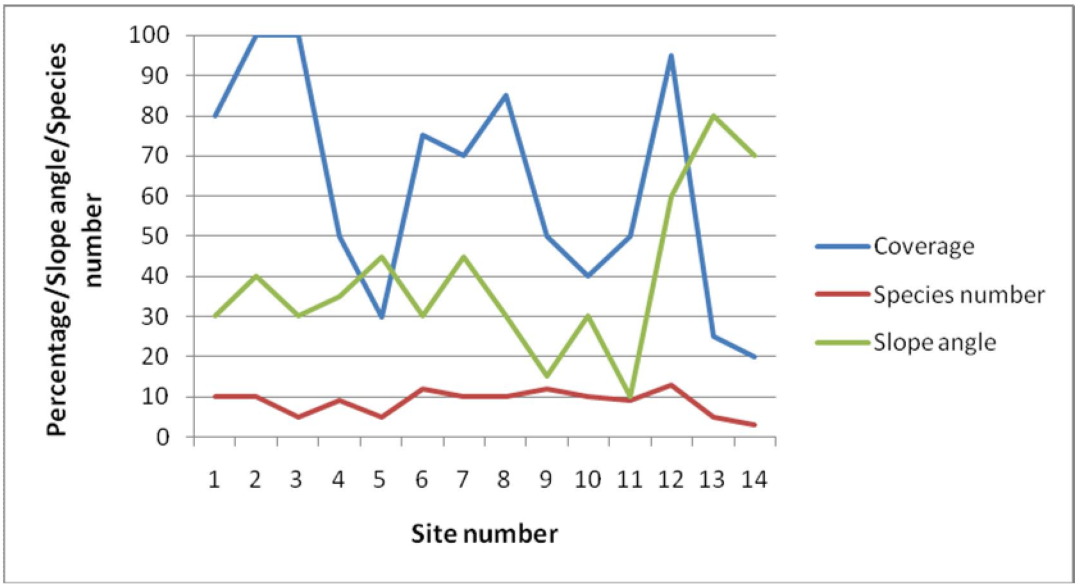

Figure 13. The data of coverage, species number and slope angles of transect 2.

The average records display that overall coverage of the transect is 62.14%, with 70% at the first five, 64% at the following and 47.5% at the last four sites with some extreme quantities of 25% and 100% (figure 13).

Species richness shows a rather standard line with an average 9.58 species. The less abundant site consists of 3, and the more diverse one of 13 identified plants. The average amount of species is the highest of the middle section between 1910-2082 m with almost 10 species, whilst both the initial five and the highest four locations show similar data with an approx. 7.5 plants (figure 13).

The vegetation distribution also tends to be similar with the first transect. The first three sites at the altitude of 1730-1790 m comprise of *Pinus mugo* and its related plants similarly to transect 1, nonetheless *Rhododenderon hirsutum, Salix retusa* and *Picea abies,* and to a smaller extent *Mercurialis perennis, Alchemilla vulgaris, Soldanella alpina and Carex ornithopada* also appear at some of the sites. However, the dominant grass species, which cover the majority of the quadrate's area beside *Pinus mugo*, are *Carex sempervirens, Sesleria albicans* and at a lower rate *Carex firma*.

At the next six examined locations (1870-2060 m) *Erica Carnea, Carex sempervirens, Sesleria albicans* exist with less abundant but occurring *Alchemilla alpina, Daphne striata, Festuca pumila, Galium spp., Gentianella ciliata, Hippocrepis comosa, Potentilla anserina* and *Veronice chamaedrys.* The last site also contains one of the alpine species of *Androsacea helvetica*.

The principal species between 2080-2150 are *Silene acualis, Salix serpellifolia, Ranunculus alpestris* and *Carex firma* with occasional coverage of *Festuca spp., Poa alpina, Primula glutinosa, Taraxacum officinale, Thymus praecox* and *Veronica aphylla*. Additionally, *Ericae carnae* was found at the site of 2150 m with 25 % coverage. While the sites between 2080-2115 m can be described by low slope angle categories (10^o and 30^o), average species richness (9.5) and 40-50% coverage, the highest site among the three discussed ones has the highest plant biodiversity with 13 found species and 95% vegetation coverage, nonetheless, also the steepest, 60^o slope.

The last two quadrates are situated in 2180-2210 m with almost vertical cliffs, 3-5 number of species and the smaller degree of coverage with 20-25%. Here both snowbed and alpine species exist, namely *Saxifraga azoides, Saxifraga androsacea, Saxifraga aphylla, Pritzelago alpina, Dryas octopetala, Sedum atratum* and moss species.

4.6.5. Transect 3

Transect 3 is at the Eastern section of the Nordkette's investigated area and includes 14 quadrate sites of an approximate 700 m between 1724-2200 m. The average microtopographical slope angle of the transect is 40.32° with a gradual increase until site 10, where the data indicate a more moderate 10° steepness, likewise at the last site, which also differ from the previous values (figure 14). However, the general trends of the slope angle at the first and second five sites as well as the last four sites are almost identical to transect 2 (33°, 36° and 55°).

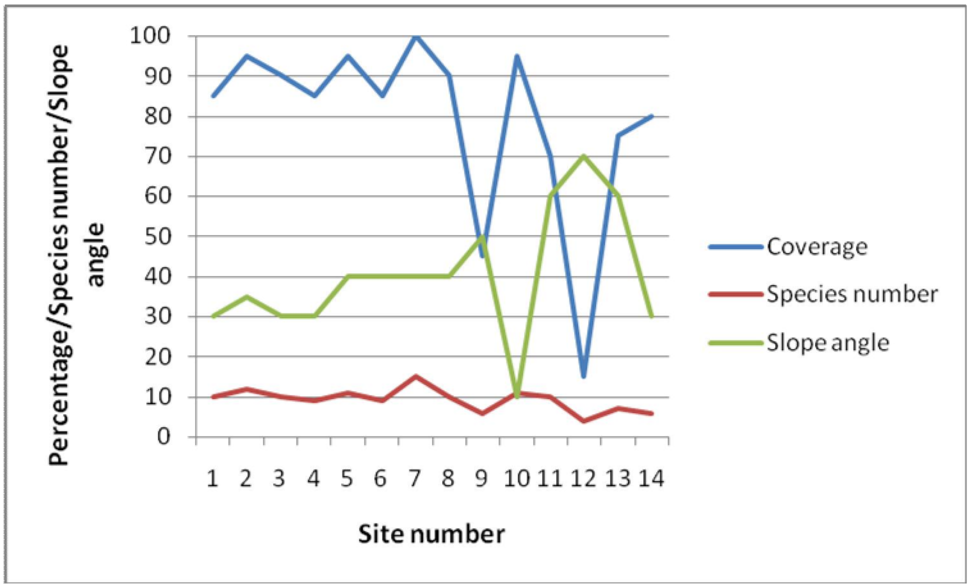

Figure 14. The values of coverage, species number and slope angle of transect 3

The coverage of the sites are fairly unique representing similar values at the first 8 sites, with a sharper change at the ninth site with a decline of 45% compared to the average of the previous eight ones. The last five locations' records are 67% in average with a significant reduction to 15% at site 12 (figure 14).

Species richness is rather steady with an average 9.2 plant species. More abundant sites can be detected at lower altitudes, however, the maximum of 15 species can be found at the middle of the transect. At the highest elevation, species number decreases and the last three sites only consists of 4-7 species in contrast with the average 10.4 of the first sites (figure 14).

Vegetation distribution at the first site can be described by the spread of *Juniperus communis ssp. alpina, Erica carnae* and *Carex sempervirens*, which varies from the next six sites where *Pinus mugo* is the most dominant species with other abundant representatives, e.g. *Sesleria albicans, Carex spp., Alchemilla alpina, Daphne striata, Gentiana spp., Lotus corniculatus, Poa alpina, Ranunculus montanum, Pulsatilla vernalis, Rhododenderon hirsutum, Scabiosa lucida* and *Soldanella alpina*. Furthermore, at two of these sites *Erica carnae* also occupies a significant area.

The following sections are slightly more difficult to homogenize. Site 8 can be characterized by similar values of the previous quadrates, although the major species differ. This site is mainly covered by *Valeriana saxatyllis, Rhododenderon hirsutum, Erica carnae, Senecio doronicum and Festuca pumila*, while Site 9 at 2010 m height is mostly dominated by *Globularia cordifolia* and *Sesleria albicans* and characterized by 6 species, 50^{o} and 45% coverage. The records of the following site typify 11 species, most importantly *Carex sempervirens, Myosotis alpestric, Bartsia alpina, Persicaria vivipara, Taraxacum officinale* and *Trifolium praetense*. The attributes of this specific quadrate display a very low, only 10^{o} slope angle and 95% coverage.

Site 11-13 at the height of 2080 and 2200 m can be generally described by steeper slope angle of average 63^{o} and similar grass and alpine species associations although site 11 have both higher coverage and species richness values. Here, *Salix serpillifolia* and *Agrosistis alpina* are the major species that occur together with *Valeriana saxatyllis, Draba aizoides, Carex firma* and *Arabis alpina*. Site 12 has extremely low values in species richness (only 4 species) and coverage (15%). At this point the same grass species occur with the additional existence of *Androsacea alpina* and *Saxifraga paniculata*, whilst site 13 with a remarkably high level of coverage (75%), nevertheless, not much more elevated species number (7). At this location *Sesleria albicans* rules the territory with *Salix serpillifolia, Minuartia gerardii, Festuca pumilla* and *Veronica aphylla.*

The slope angle of the last site is more modest with 30^o, with 80% coverage and 6 species. Here, 65% of the quadrate is occupied by grass species, mostly by *Carex spp*., whilst the other dominant species is *Silene acaulis*.

4.7. Future projections

If warming tendency continues similarly to previous years, it might be projected that woody-plant species move upwards on slope to seek for more favorable temperature conditions (Dirnböck et al. 2003; Dullinger et al. 2003). Accordingly, a model of the future distributions of the tree species might be estimated based on temporal temperature fluctuation and the already occurring upward shift with two fundamental assumptions. Firstly, it is assumed that the timberline shift is in direct proportion with temperature increase and second, this proportionate increase was continuous in the investigated period of 1946-2005.

In order to construct this model the average tree line position and its calibrated temperature of 1946 (1756m - 1.722^{o}C) and 2005 (1780 m - 2.44^{o}C) are utilized as well as the average tendency of the previous years' tree line shift (24 m/0.718 ΔT, namely 1m/0.0299 ΔT). For the estimation of the altitude of the average timberline in 2050, climate scenarios of 1-2^{o}C and <2^{o}C are taken into account and added to the calibrated 1961-1990 average temperature values, calculated from the mean temperature data of Zugspitze, Patscherkofel and Innsbruck on the ground of the 0.65^{o}C/100 m gradient. Hence, in the case of 1^{o}C warming, the lowest limit of the climate projection, the average timberline may be positioned between 1806 (ranging between 1801-1811 m with the ± 10% alteration of the ratio), while in the case of 3^{o}C temperature increase it may reach 1873 m (ranging between 1861-1885 m with the ± 10% alteration of the ratio) (figure 15). However, it has to be emphasized that this model exhibits the potential average timberline's ranges, therefore, does not include the potential modification for instance, of the higher situated groups.

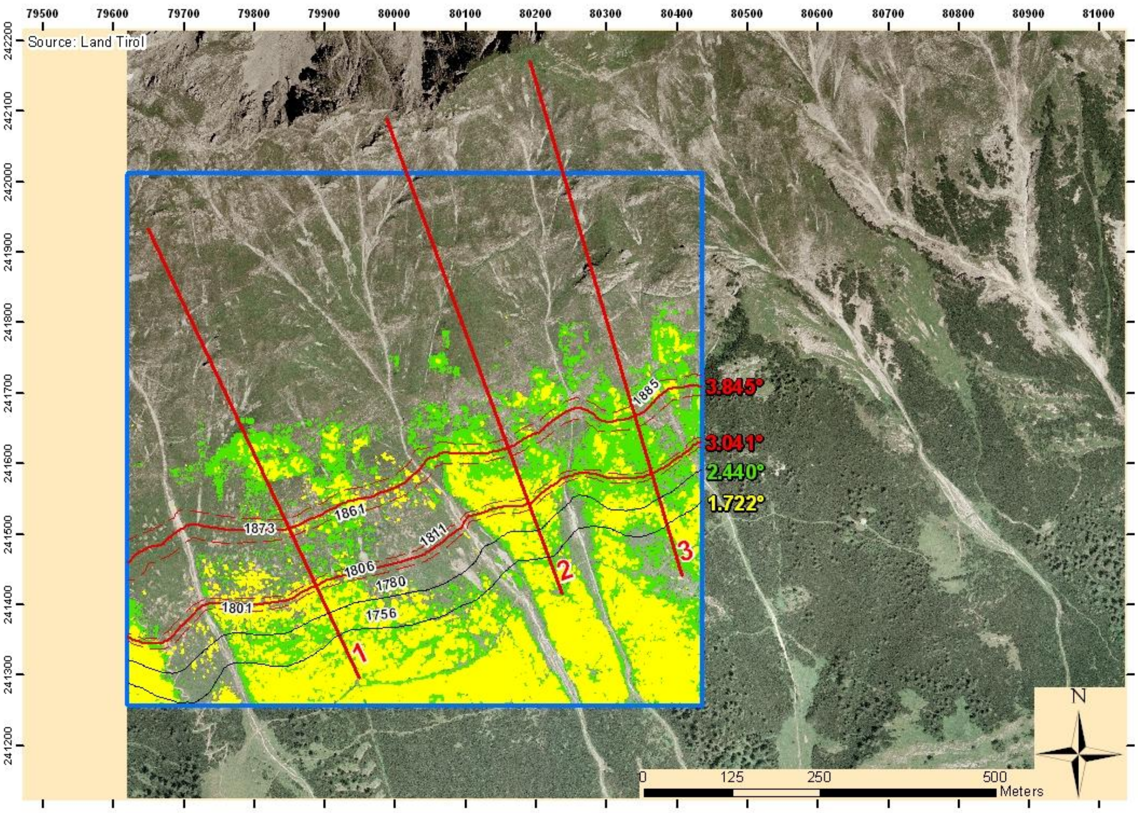

Figure 15. The average position of the tree line in 1946 (the lowest contour line) and in 2005 (the next line) with yellow and green numbers indicating the mean annual temperature of that year. The above placed two contour lines present the potential future timber based on strictly by the climate scenarios to 2050 (Land Tirol).

For the completion of the model, the probable distribution patterns of the grassland belt and thus, the remaining habitats of the snowbed and alpine communities, might be assumed on the ground of some previous studies and the results of the fieldwork. Pauli et al. (2003) argue that grass species have already established themselves successfully at higher regions as a result of climate change, reducing the area of the potential habitats of the alpine communities. They also add that the prevailing factors in their upward motion, besides climate warming, is topography since grasses tend to have less capacity for the succession of the steeper cliffs. This statement can also be confirmed by the fieldwork data because grass species number declines gradually with higher slope angles above 2100 m, where alpine species also tend to appear, whereas alpine species become dominant on slopes steeper than 50^{o} (figure 16).

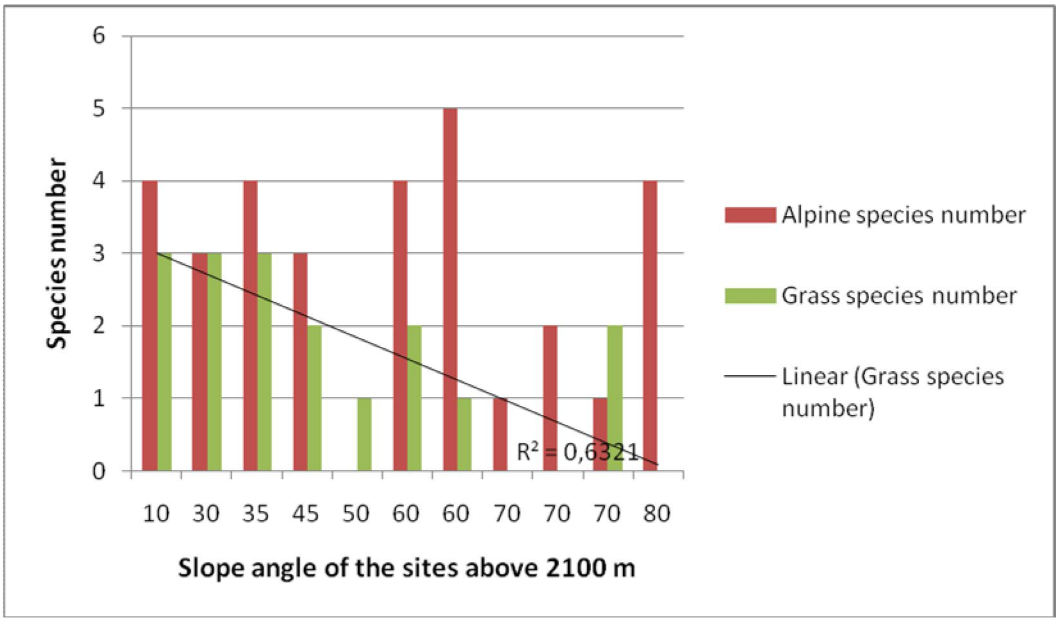

Figure 16. To analyze the relation between alpine and grass species number and slope angle, all of the sites above 2100 m are evaluated in terms of the number of alpine and grass species and slope angle. Grass species show a significant decline above 50o where mostly alpine species dominate.

Therefore, although the exact rate of grass migration is not known, it can be presumed that grass species invade the alpine regions more intensively with the higher rate of climate warming and occupy the habitats of the upper vegetation zone, whereas connected steep sites above 50^{o} may provide microhabitats for the alpine plants. This projection, besides previous studies (Grabherr et al. 1994; Pauli et al. 2003; 2007; Erschbamer at al. 2009), can also be supported by the historic data alteration (*Sesleria albicans* and *Carex spp.* upper occurrence limit was detected to be 2100 m) and the fieldwork documentation.

5. Main findings of the study

5.1. Climate warming of the region

As Auer et al. (2008) point out an overall temperature rise has been experienced in the last 50-100 years in whole Austria with insignificant regional variations. Especially winter temperature warming was observed with peaks in 1920, 1980 and 2000, while summer temperature increased until the 1950's and 1980's, after which moderate cooling phenomena were noticed (Beniston 2005; Auer at al. 2008). This wide-ranging tendency meant an average 1-2^{o}C degree amplification of the atmospheric temperature throughout the alpine region since the beginning of the last century (Haeberli and Beniston 1998).

The long term temperature data of the nearby mountain meteorological station of Zugspitze mainly support this statement with the exception of the coldest year of the century in 1945 (with the mean annual temperature of -7.71^{o}C). Despite of this, the 1940's are regarded being a warmer period (Beniston 2005). On the other hand, the following years are in fact much warmer until the 1950's. Also, the Zugspitze's data show an average 1^{o}C increase in the mean temperature from the beginning of the twentieth century until the end of it, which also signify a current milder climate of the Alps. Furthermore, even if a broad-spectrum trend of temperature fluctuation seems to occur with gradual ascent and decline in each 5-10 years, the difference between the maximum and minimum of the two values decreases as well as the rate of them by the end of the century, which also suggests the warming of the area.

The records of Patscherkofel station do not illustrate such a straight-forward trend in climate warming, although the mean annual temperature generally increases. Yet, in contrast with the described and expected warming winter climate, the mean minimum temperature declines in Patscherkofel, which is analogous with the documentation of the Seegrube station that also shows results with continuously cooling winters. This tendency might be ascribed to the short period of the documentation and the exceptionally cold years of 2003-2005, which could also be the cause of the distortion in Patscherkofel's data in addition to the averaged values of the phases of 1951-1960 and 1961-1990.

Nevertheless, if we consider the longest datasets of Zugspitze and the mean annual temperature of Patscherkofel, both representing temperature increase, in addition to the 100 year-old temperature records in Innsbruck (the closest town to the surveyed area that shows around 1^{o}C rise 1900-2008), warming tendency of the site might be taken for granted with an average growth of 1^{o}C since the 1900's, which is calibrated from the temperature values and the 0.65^{o}C/100 m gradient.

5.2. The vegetation alteration of the site

5.2.1. The changes of the tree line 1946-2005

Primarily based on the remote sensing data, the most important finding of the analysis displays that there are significant changes of the vegetation in respect to both the woody plant-covered area and the related tree line position during the period of 1946-2005. The mostly *Pinus mugo* dominated area expanded by 22 737 m^2, while its upper elevation limit also ranged to higher regions by 24 m. The explicitly dominating *Pinus mugo* not only did increase its territory by more than 25% between 1946 and 2005 at the higher sections, and migrated to higher altitudes, but also filled out more intensely the non-covered patches below the timber line, which indicates a general spread at lower sites, as well. The coverage distinction of the shrubs between the years of 1946 and 2005 shows that *Pinus mugo*, potentially with its plant association, widened the homogenous tree line ecotone as well as the areas of the previously existing higher situated patches and moved upwards on the slopes.

5.2.2. *The major contributing and limiting factors in the alteration of the tree line*

The general tree line and tree covered area tendency of the surveyed site is therefore generally increasing, which is in line with some other studies that support the hypothesis of the timberline's upward shift, along with the expansion of woody-plant covered area primarily due to climate warming (Dirnböck et al. 2003 and Dullinger et al. 2003; 2004; Wallentin et al. 2008). These research specify particularly *Pinus mugo* as an invasive and fast moving species attributing its advance to the more favorable warmer conditions, which allow the shrub to occur at higher regions, since the major control of its growth and fecundity is likely to be closely temperature related (Dullinger et al. 2003).

Alternatively, there are other scientific findings, as well. For instance, Gehrig-Fasel et al. (2007) rather emphasize the role of land use change instead of climate warming because their investigated area experienced intensive deforestation and grazing pressure. Consequently, they consider land abandonment as the major driver of reforestation, which could have been the case also at the examined site, and which would elucidate Pinus mugo's restricted occurrence (up to 1940 m) in contrast with the Nordkette's general altitudinal limit of 2030-2050 m (Pitschmann et at. 1970; Grabner 2000). However, long term land use records were not available. Conversely, the likely 1^{o}C increase of the mean temperature at the site probably triggers alterations in the vegetation, as well as shown by for instance, Dullinger et al. (2003) and Wallentin et al. (2008).

On the other hand, the results do not always indicate an upward shift. In the proximity of transect 1 the opposite process can be observed, namely the loss of woody plants, which were presumably *Pinus mugo*, as well. Two probable reasons can be given for the disappearance of the shrubs. Firstly, land use practice, more specifically traditional grazing, can cause the removal of the plants by injuring them, while the extension of alpine grasslands is expected to occur (Dirnböck et al. 2003). Nonetheless, this cannot explain why the deforestation took place right at that exact spot and not at the other sections, and why the higher situated upper groups survived the grazers. Unfortunately there is no information regarding long term land use at the site.

Secondly, perturbation could have occurred as the discussed area is closer to a valley side, where avalanches and water and snow with transported materials usually slide down. The more mobile silt and scree areas along with the falling bulk of snow and water are more probable to wipe out the woody vegetation as avalanches and landslides are very common at this area (Gartner 2000). This would also clarify why the upper patches were preserved that occur in a more sheltered place further from the valley side.

In spite of this precedent, the regular trend indicates an overall upward movement. However, even within its range there are potential limitations of the upslope movements, as it was experienced on the field (figure 17). At many sites, *Pinus mugo* species were found dry and removed from the ground, which could be due to the regular perturbation of the area by avalanches, landslides and sudden flows of water and snow. However, in many cases, although not in all (figure 17), the trees were not far from their presumed exact living positions. Even on steeper slopes their roots contained still a large amount of ground, which can imply the incapability and shallowness of the soil to hold the mature tree and its extended roots on acclivities, so after reaching a certain size or weight, the plant simply falls out or becomes more vulnerable to disruptions.

5.2.3. Species distribution and species interactions in the tree line

Still, the general pattern implies migration towards the upper side, which is partially climate related, particularly in the case of *Pinus mugo* (Dirnböck et al 2003; Dullinger et al.

Figure 17. The pictures indicate three removed Pinus mugo specimen. The above two shrubs were found next to their living positions while the below one was probably carried by the snow flow.

2003). This process of so-called shrub invasion, predominantly on carbon slopes, can mean a decline in territory of the upper habitats, especially of subalpine grasslands. *Pinus mugo* at this altitude has a lack of competition by other shrubs and trees (e.g. the then more wide-spread but today lessened *Pinus cembra*) (Dullinger et al. 2003) so it can spread without difficulty.

The field data show corresponding results illustrating *Pinus mugo* as the most dominant species at the lower sites, typically up to 1950 m, similarly to other descriptive research (Pitschmann et at. 1970; Grabner 2000), although they place its upper limit higher to 2030-2050 m. Grabner (2000) states that *Rhododenderon hirsutum* and *Erica carnae* persist with *Pinus mugo* as well as with additional species, such as *Sesleria albicans, Phyteuma orbiculare, Campanula scheuchzeri* and *Daphne striata* until 2050 m, after which they form a dwarfheath shrub with *Salix spp.* and *Dryas octopetala*. Pitschmann et al. (1970) likewise point out that from 2030 m *Erica carnae* is the dominant in association with *Rhododenderon hirsutum, Arctosstaphyllos alpina* and *Dryas octopetala*. The field records also display that *Erica carnae,* although identified at some of the same sites with *Pinus mugo,* can be distinguished as another belt above the shrub zone. Conversely, *Rhododenderon hirsutum* were scarcely found with *Pinus mugo* and also above, and generally throughout the sections, even though it is referred to as one of the principal species of Hafelekar, growing both in the subalpine and alpine zones (Pitschmann et al. 1970). In spite of this, *Rhododenderon hirsutum* was detected only at few sites, and was seen mostly next to the abundantly growing *Pinus mugo,* closer to hiking tracks or clearings, similarly to the other woody species, e.g. *Picea abies*, *Salix spp.* and *Juniperus communis ssp. alpina,* which also persist along with *Pinus mugo,* though, they cannot be found in larger abundance in contrast to the shrub. This fact might to some extent be explained by the invasive characteristics of *Pinus mugo*. Yet, grass species, mostly *Carex spp.* and *Sesleria albicans,* which dominate above the *Pinus* zone, manage to co-exist with the shrub, probably most successfully. However, they are probably the remains of the previously existed grasslands and will be potentially affected by the aggressive succession of the tree.

5.2.4 Temporal alteration of the upper belts of Ericacae and the grasslands

According to Pitschmann et al. (1970) and Grabner (2000), above the Pinetum mughi zone in 2030-2050 m, the major plant species are typically composed of *Erica carnae*, *Rhododenderon hirsutum*, *Dryas octopetala* and *Arctosstaphyllos alpina.* Parallel vegetation pattern can also be observed from the field documentation of *Erica carnae*'s growth between approx. 2000-2100 m, although the species could be noticed at higher regions, as well. However, the associated above mentioned species were mainly missing with the exception of *Dryas octopetala*. Instead, *Sesleria albicans*, *Carex firma*, *Carex sempervirensis* and other grass species grow in larger quantity, which may indicate the expansion of the grassland. Grass plants, similarly to *Pinus mugo,* can also behave as invasive species, principally in the higher zones. Their biological traits allow their succession in quick sward and soil formation compared to high mountain vascular plants, which grow less rapid and react slower to modifications (Pauli et al. 1999). This might be one of the reasons why grass species occur throughout the site in such large quantities, but may raise the question, why they appear in such a high number also below and above their described extension.

5.2.5. The governing controls of the grasslands' distribution

The more significant spreading of the grass species on the one part can be explained by the possibility of historic grazing in the area, which may contribute to the maintenance of such a high range of grass species' extension (Tivy 1982), along with the Pinus mugo's limited expansion. However, grazing would not explain the continuous upward migration of *Pinus mugo*, which can be easily damaged by grazing (Dullinger et al. 2003).

On the other hand, smaller soil slips and landslides are very frequent phenomenon in the Alps (Moser 2002). The effects of them could be evidently seen also *in-situ* in the formation of bare land flows with still mobile ground particles and steep, almost vertical micro slopes, with hardly any vegetated coverage (figure 18). These perturbed sites might explain the more common abundance of grass species, which have quicker growth and reproduction rate, and thus, also have a high potential in colonization of non-vegetated sites (Pauli et al. 2003).

This trend may also explain why there are sites in lower regions with smaller vegetation coverage, and at the other sites not detected species (e.g. *Tussilago farfara* that has not been described in Hafelekar in the previous studies) with high frequency of grass species. However, these changes are mainly determined by various disruptions and the resulted micro scaled geomorphological patterns, which can often be very temporal and consequently, complicated to examine. In spite of this, as it can be seen, disturbance, microtopography and soil depth seem to have a major role in vegetation patterns, which should be further assessed to have a broader perspective about vegetation dynamics.

5.2.6. The peak vegetation and their determining factors

Comparing the recent data to the historic records, some probable tendencies can be drawn regarding the alpine belt. Some of the upper regions are mostly occupied by grass

Figure 18. Landslides and mass movements in around 1800 m.

species, although in the historic records grasslands mostly occupied zones below 2100 m (Grabner 2000). However, grass species, especially *Carex spp.*, *Sesleria albicans* and *Festuca spp.*, were found to be one of the major vascular plants also at the higher areas. Alpine species also cover sites on a higher scale, particularly in rocky and cliff environments. On the more mobile and scree habitat, closer to the peaks, grass species also grow, although to a lesser extent. According to Pauli et al. (2003), in the process of invasion and colonization of the upper belts by grass species, the scree and barer and steeper rock surfaces have a major function: while flatter ridges, which are less interrupted by the mass movements of the unstable slopes and debris falls, can serve as a potential microhabitat for the grasses to be established, less permanent, disturbance exposed micro and macro forms are more likely to prevent the succession of them. Therefore, this may indicate that the abundance of grass species is restricted to these "stepping stones", the more stable ridges (Pauli et al. 2003). Nevertheless, grass species' presence in the higher regions is already significant. This may be further enhanced due to the climate induced reduction of snow cover and perturbations' frequency that could contribute to more stable soil formation (Pauli et al. 2003).

5.2.7. Alpine and nival species

In accordance with the temperature and vegetation data, the question can be raised: if temperature, and along with it competition increase at such a remarkable rate, why do most of the mentioned species from the first part of the last century occur at the sites mainly at similar heights, whilst some species from the lower elevation cannot be found presently? Even the most sensitive snowbed species (*Saxifraga spp.*, *Arabis caerula* and *Ranunculus alpestris*) identified in the studies of Rübel (1911), Lüdi (1921) and Jenny-Lips (1933) (Grabner 2000) could be seen at the site in addition to other representatives (*Silene acualis, Salix serpillifola* and *Arabis spp.)* in spite of their vulnerability to temperature warming and less extended habitats (Beniston 2003; Huelber et al. 2006). The existence and abundance of these species could suggest that warming climate do not have such a high impact on these more sensitive species.

Nonetheless, the current distribution of the alpine species may be endangered, not directly by climate warming, although the <2^{o}C increase will certainly confine their ranges, but by the accelerated rate of grass invasion (Gottfried et al. 1994; Pauli et al. 2003). At many sites, microtopoographical slope angle increases sharply, which means in some cases an often vertical bare cliff surface. This can serve as microhabitats, principally inhabited by some of the alpine and snowbed species (e.g. *Androsace spp., Saxifraga spp.*). This restriction of some of these plants may potentially be the result of the fast growing grass species' (e.g. *Sesleria albicans*) excellent competitive abilities (Walker 2000). As it was mentioned before, grass species are more likely to establish themselves on the more stable and flatter habitats, invading the alpine species' habitats there. They are less successful on steeper slopes, however. This was also observed on the field where grass coverage was more extended on slopes with smaller gradient (figure 16), whereas on scree and rocky habitats they occurred more in patchy forms (figure 19). Therefore, these steep, perpendicular rock surfaces and scree formations are the most likely to provide refugias for the alpine and snowbed communities.

5.3. Potential projections of the site's floral distribution for 2050

If only climate change is considered as the major factor for the tree line and area expansion of *Pinus mugo*, (in the case of grass species also slope angle), and if it is presumed that due to the projected climate warming vegetation will also be altered, as it has seemingly been before,

Figure 19. The images indicate that on bare rock surfaces and scree areas grass species are limited, while on less steeper slow they have already established a dense sward formation.

a future outlook can be envisaged based on the two climate scenarios of 1-2^{o}C and <2^{o}C and the slope gradients (figure 20).

5.3.1. Projections for 1-2^{o}C atmospheric temperature increase

If temperature continues to augment with 1-2^{o}C by 2050, the coverage of *Pinus mugo* will expand and shift upwards until approx. 1820 m, correspondingly to the grass species belts, which will also be capable of faster movements due to their biological characteristics (Pauli et al 2003). *Carex spp.* and *Sesleria albicans,* along with *Poa alpina* will probably spread its coverage in higher regions, with the exception of the elevated gradient rock cliffs.

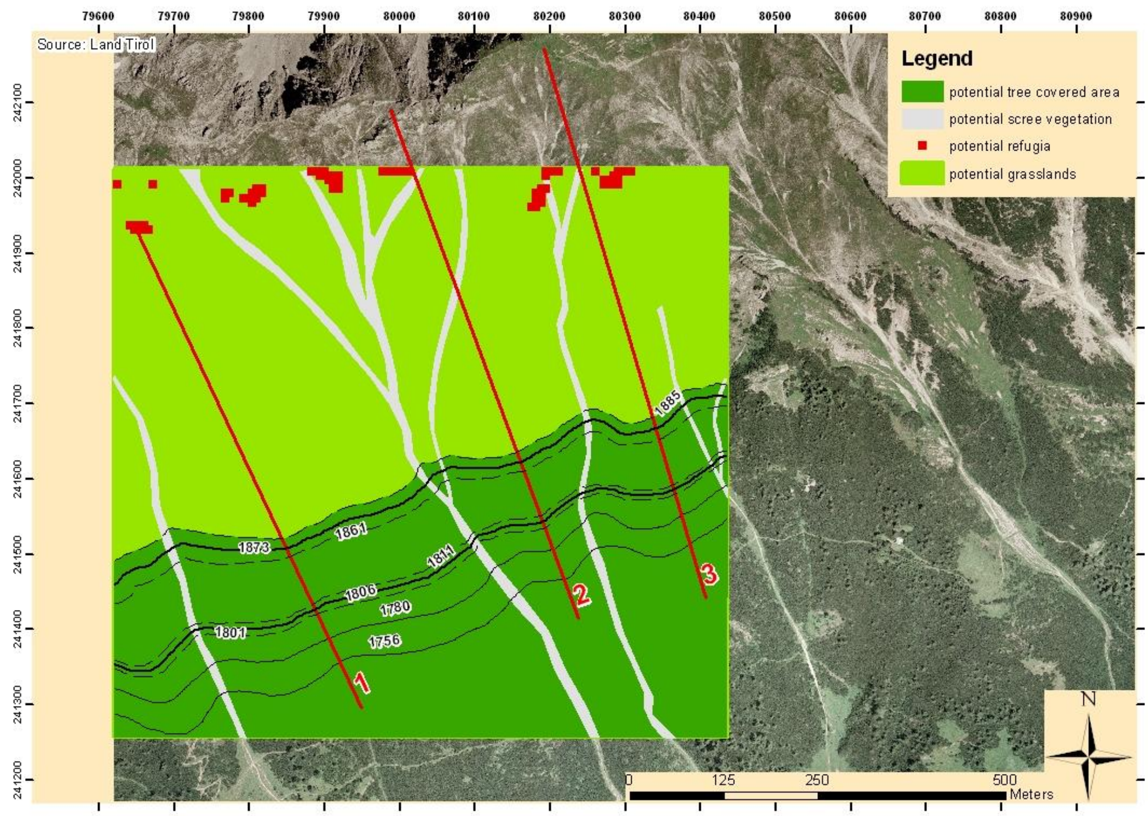

Figure 20. The potential distribution of the grassland belt, the potential maximum range of the average timberline, scree vegetation and refugia areas for the alpine and snowbed species in 2050 based on the tree line and digital elevation model of the area (Land Tirol).

5.3.2. The <2^{o}C climate warming temperature scenario

If climate rises in an even more accentuated manner, the main species of the tree line ecotone and the grassland belts will continue to establish themselves at an even more considerable level. *Pinus mugo* might reach the average altitude of 1880 m whilst grass species are also projected to spread at a more significant level. Also, the area of heath land and dwarf shrub region of *Erica carnae* and *Rhododenderon hirsutum* may decrease inversely with the elevated distribution of *Pinus mugo* and the Sesleria-Caricetum assemblages.

5.3.3. The effects of potential alterations

The prediction of the future floral zones' position reveals that the ranges of the alpine and snowbed communities as well as the dwarfshrub belt are likely to shrink, whilst the belts of grass species and *Pinus mugo* will probably escalate. These processes may have some further consequences:

- *Pinus mugo* is likely to advance upwards quickly ranging up to 1880 m, and by that displacing the above situated dwarf shrubs and grasslands. The advance of Pinus mugo, therefore, can significantly reduce alpine biodiversity. In addition, this pine species can acidify the soil limiting the habitats for even less species (Bronick and Mokma 2005). On the other hand, *Pinus mugo* can contribute to soil stabilization (Stützer 1999).
- Grass species may also supplant the dwarfshrub heath in lower regions and the alpine species next to the peaks. However, with the further extension of the *Pinus* zone, they may occupy less area, as well. Grass species, while homogenize the biodiversity, may also contribute to the reduction of mass movements by soil stabilization (Pauli et al. 2003).
- In the gradually reducing alpine and Ericacae belts situated protected and medicinal plants (*Erica carnae, Rhododenderon hirsutum, Daphne striata, Gentiana spp, Primula spp, Androsace spp., Saxifraga spp., Silene acaulis* (Jaitner 1991)) may experience significant reduction or they may extinct. This species loss may trigger further changes in the ecosystem by affecting the fauna and diminishing genetic resources (Sarukhán and Whyte 2005).

5.3.4. Limitations and amendment suggestions

These projections are based on climate warming and on previous migration's trends as well as on macrotopographical slope angle to predict the vegetation's outlook by 2050. However, there are some shortages of these predictions that have to be noted. Firstly, the temperature data of the site were calibrated by the average values of the nearby meteorological stations. This is most probably resulted in some distortions of the outcomes as microclimate and soil temperature, especially in densely vegetated areas, can significantly differ from the calculated averaged air temperature (Dullinger et al. 2003).

Also, in this study mainly the physical attributes were taken into account, though it is widely accepted that biological factors, e.g. species interactions, growth and reproduction rate and germination speed, define vegetation distribution at a large scale and can be just as vital as the physical factors (Beniston 2003; Holzinger et al. 2008; Pauli et al. 2003; 2007). Furthermore, no information on historic land use was analyzed, which can be an additional key driver in the development of the vegetation zones, especially in the timber line dynamics (Gehrig-Fasel et al. 2007; Nagy 2006; Wallentin et al. 2008). Besides, perturbation variant, microtopography and the soil depth of the area were not measured during the study, although they probably have importance in the vegetation belts' dynamics, as it was observed. Although, these values, specially the regular landslide induced constantly changing microtopography, could be difficult and also costly to measure, it might be worth considering it in further assessments.

The projections of the future distribution cannot reflect very precisely the distribution of the species since it considers only climate change, macro slope angle, previous and recent patterns. On the other hand, they can provide a rough estimate of the prospective appearance of Hafelekar and the extension of certain species in respective of climate warming, which is supposed to be the main determinant of future vegetation (Pauli et al. 1996; 1999; 2001; 2003;

2007; Beniston 2003; Wallentin et al. 2008; Parolo and Rossi 2008; Grabherr 2009). However, this study fulfils its main task to guide conservation activities by providing a rough estimate about the potential endangered species and areas of their preservation.

5.4. Implications

The methodology and the results of the projections of the vegetation distribution by 2050 in terms of two various climate scenarios can provide wider implications for both theory and practice.

5.4.1. Recommendations for theoretical improvement

As it was mentioned before, the methodology of assessing alpine vegetation patterns could be amended by the inclusion of microtopographical features at larger resolution (m or cm accuracy would be preferred) to understand perturbations', especially soil erosion's role in vegetation growth and distribution. Moreover, the analysis of the relations between soil depth and vascular plant species, in particular in terms of woody plants, might be proven beneficial, although it is not particularly mentioned in the vegetation modeling studies (Gottfried et al. 1999; Dirnböck et al. 2003; Dullinger et al. 2003; 2004).

5.4.2. Practical suggestions

The study has its main implication from a biodiversity conservation point of view. The constructed model (figure 20) appoints the wide-spread extension of the *Pinus* zone and the grasslands, while indicates only few selected areas as possible shelter for the upper belts' assemblages. This could have several consequences from a plant conservation point of view in the Hafelekar. Numerous, already protected and endangered species of the site and Nordkette (e.g. *Erica carnae, Rhododenderon hirsutum, Saxifraga spp. Androsacea spp., Silene acaulis, Daphne striata* (Jaitner 1991)), may experience further reduction in their habitat or even extinction due to climate warming and the advance of the grass belt and the *Pinus* zone. Therefore, some steps to control the invasion species and to protect the alpine and *Ericacae* habitats may be considered:

- *Pinus mugo* may be controlled carefully by traditional alpine grazing or logging (Dirnböck et al. 2003), although their role in soil stabilization should be considered.
- Grasslands may also be managed by alpine grazing, while a designated *Ericacae* zone may be provided protected by fences against the grazers.
- Cliffs above scree sectors, which can prevent the migration of the faster grass types, provide safer habitats for alpine and snowbed communities. Thus, these habitats should receive special attention. Crucially, when refugia areas are created to maintain the alpine biodiversity, cautious location selection is essential with the preference of connected rocky and steeper habitats, preferably at higher mountains.

5.4.3. Wider assumptions

In the condition that the main findings of the prediction of this study, in line with the future vegetation modeling research (Gottfried et al. 1999; Dirnböck et al. 2003; Dullinger et al. 2003; 2004) are proven to be correct, the areas of the forests and grasslands can be expected to increase. This would not be that unique in Earth's history, since in the Holocene, the tree line of the Calcareous Alps is approximated to be 400 m higher than today (Dirnböck et al. 2003). However, the recent climate warming is presumed to be more rapid and also human-affected (Beniston 2003; Aerts et al. 2006), which has and may have extended impacts on humans in the future, as well.

If *Pinus mugo* and the grassland belt managed to invade the upper alpine and nival zones and stabilized the soil as Pauli et al. (2003) suggest, this may lead to alterations in water and land movement meaning lower frequency of land slips and mass movements and less run-off potential.

This dwarf shrub may not be the only woody species that has been advancing towards higher altitudes. At the lower limit of *Pinus mugo*, other tree species e.g. *Picea abies, Larix deciuda* and *Pinus sylvestris* are also likely to become more successive, and gain ground by migrating upwards (Dirnböck et al. 2003), which might suggest the additional ascend of the non-coniferous tree species (*Fagus sylvatica, Betula pendula*, *Acer pseudoplatanus*, etc.). Consequently, it may be deduced that *Pinus mugo* might have not gained area in total, only at the higher sites because the below situated species might have also occupied the previously *Pinus mugo* inhabited areas.

However, if it is estimated that tree coverage may increase in the future due to much milder climate (<2^{o}C) also at the other sites of the Alps (Theurillat and Guisan 2001), it might be suggested that in theory, the average expansion of forested areas may increase. This could indicate a creation of a larger carbon sink, which could play a role in future CO^2 scenarios.

6. Conclusion and recommendations

6.1. Summary of the main findings

To conclude we can say that the regional warming of the Austrian Alps, the probable 1^{o}C temperature increase in the last 100 years, presumably has had an impact on the vegetation of the site. This may have caused numerous alterations in species distribution and species interactions compared to previous stages. However, it is important to state that these changes may not be explicitly attributed to climate change. There are other biotic, abiotic and human-induced processes that define vegetation dynamics. At the surveyed site, probably land use change, disruptions and biological factors have partially contributed to the appearance of the vegetation's recent stage. On the other hand, it is most probable that climate change is the key determiner of species distribution and species composition, which have showed some relevant alterations:

- *Pinus mugo* has shown a significant upward shift and extension in 60 years. Compared to the 1946's stadium, it has exceeded its territory with more than 22 000 m^2 and an average 24 m elevation increase at the surveyed site.
- The extended ranges of the grasslands, compared to the previous century's description, also indicate that grass species, specifically *Sesleria albicans* and *Carex spp.*, are more wide-spread and move upwards.
- The expansion of Ericacae belt has been probably reduced potentially due to the rapid invasion of *Pinus mugo* and the grass species.
- Alpine and snowbed communities may have lost habitats due to the grass invasion. Although most of the previously recorded species persist, they are restricted to steep cliff areas where grass species cannot establish themselves so effectively.

Based on these alterations and the rate of them, it may be presumed that by 2050 the view of the site may be further modified if temperature rise continues. It is assumed that:

- *Pinus mugo* will continue to migrate towards more elevated regions and may reach an average 20-100 m higher extension than today depending on the climate projections.
- Grass species will also enlarge their ranges occupying more alpine and snowbed habitats.
- The Ericacae belt will shrink further.
- Alpine and snowbed assemblages will be limited to few connected cliff areas, which cannot be colonized by grass sward formations.

6.2. Implications and recommendations

These potential modifications in the vegetation may trigger further alterations in the ecosystem, which may also have human aspects.

- *Pinus mugo* and the grass species may displace several species in the Ericacae and the alpine belt lessening the biodiversity, which may lead to reduced ecosystem services, including the loss of genetic, medicinal and ornamental resources (Sarukhán and Whyte 2005; Grabherr 2009).
- On the other hand, the quick advance of *Pinus mugo* and the grasslands may result in soil and scree stabilization, which may be beneficial in a region where landslides, floods and avalanches cause serious economic and social problems (Gartner 2000; Moser 2002; BMU 2007).

Bearing these two issues in mind, decision makers should work out appropriate conservation strategies and environmental policies before certain species are lost for good. In order to preserve some endangered species the following practical actions are recommended:

- the extension of *Pinus mugo* and the alpine grasslands may be controlled by traditional grazing.
- refugia should be created for *Erica carnae* and its assemblages. If traditional grazing is applied, sufficient fenced areas should be created for these communities in the appropriate height above 2000 m.
- The connected cliff areas are the potential habitats for the alpine and snowbed flora (figure 20). Thus, these sites should receive special focus and protection. Moreover, the here occurring species' relocation to higher situated mountains should also be considered if certain plant species cannot be found elsewhere and if conditions are suitable.

These recommendations provide some useful guidelines to preserve the alpine flora since soon certain communities or even species are very likely to disappear for good with what biodiversity lessens along with ecosystem services. These modifications also impact us in various ways, which we have to address with adequate policies and strategies. Nonetheless, conservation strategies are only drops in the bucket, which alone cannot give solution for the overall climate change issue. Only dealing with the effects of climate change will not alter the real cause of all these changes. Therefore, in addition to the question of how should we mitigate and adapt, the major question should be this: what can we do to stop climate change and along with it, its impacts, which do not only have effects on vegetation distribution but on other aspects of life, as well.

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Appendices

Appendix 1

The data of the transects

Transect 1

Site number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Plant species															
Acinos alpinus					x										
Aconitum napellus						x									
Adenostyles glabra															
Alchemilla alpina			x	5		5	15	x	10					x	
Alchemilla vulgaris						x									
Androsace alpina															
Androsace helvetica															
Anthyllis vulneria			x									x		10	
Arabis alpina															
Arabis soyeri					x										
Arctosstaphylos alpina												10			
Asplenium trichomanes															
Aster bellidiastrum															
Agrostis alpina															
Bartsia alpina															
Bellis perennis	5														
Carduus defloratus					5										
Carex firma	5	x	x							5			10		
Carex humilis					x										
Carex ornithopada	x														
Carex parviflora															

Site number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Carex sempervirens	15	x	x			30	x		x			x			
Carlina acaulis															
Cerastium holosteoides															
Cirsium spinosissimum								x							
Cyclamen purpurascens															
Daphne striata		5						x			x			30	
Deschampsia cespitosa															
Draba aizoides															
Dryas octopetala	5					x									
Erica carnae	20	x						10		5	10	50			
Eriophorum scheuchzeri				x											
Festuca pumila															
Festuca rubra					5										
Galium odoratum					5	5									
Galium anysophillon									x	x				x	
Gentiana brachyphylla						x			x		10				
Gentiana verna	x	x													
Gentianella ciliata															
Geum montanum							5					x			
Globuaria nudicaulis								x							
Globularia cordifola						30	5	5		5	30	15			
Gnaphalium hoppeanum															
Helianthemum alpestre															
Hippocrepis comosa												x			
Homogyne alpina		x						5						5	
Hylocomium splendens														x	
Juniperus communnis ssp. alpina		20													
Leucobryum glaucum						x					x			10	x
Lotus corniculatus		x				15	5			x					
Mercurialis perennis															
Minuartia gerardii															

Site number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Minuartia sedoides															
Moehringia ciliata															
Myosotis alpestris															
Pedicularis rostratocapitata															
Picea abies															
Pinguicala alpina		x													
Pinus mugo	30	40	80	30				35							
Poa alpina															
Polygala chamaebuxus	5			x						5	x				
Potentilla anserina				x						x	x				
Potentilla aurea												x			
Potentilla brauneana									x						
Persicaria vivipara															
Primula auricula															
Primula glutinosa															
Pritzelago alpina															
Pulsatilla vernalis	x	5	x												
Ranunculus alpestris															
Ranunculus montanum	5	x				x	20								
Rhododenderon hirsutum										x					
Rosa pendulina															
Rubus spp.															
Rumex scutatus					x										
Salix retusa															
Salix serpillifolia														10	
Salix waldsteiniana	x														
Saxifraga androsacea															
Saxifraga aphylla															20
Saxifraga paniculata															
Scabiosa lucida												x			
Senecio doronicum	x	x													
Sesleria albicans		15	20	35			25	30	30	20	30	15			

Site number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Silene acaulis														15	
Soldanella alpina		5	x												
Sorbus chamaemespilus															
Taraxacum officinale					5				10						
Thlaspi rotundifolium								x						x	
Thymus Praecox									x						
Trifolium pratense															
Trisetum distichophyllum															
Trollis europaeus															
Tussilago farfara															
Urtica dioica															
Vaccinium vitis idaea															
Valeriana montana															
Veronica aphylla															
Veronica chamaedrys									x		x				
Veronica fruticans					x										
Viola biflora	*x*	*x*		*x*	*x*			*5*							
Xanthoria parietina															
Altitude (m)	**1725**	**1751**	**1780**	**1809**	**1841**	**1873**	**1904**	**1939**	**1972**	**2043**	**2076**	**2110**	**2225**	**2258**	**2293**
Coverage (%)	**90**	**90**	**100**	**70**	**20**	**85**	**75**	**90**	**50**	**40**	**70**	**90**	**10**	**80**	**20**
Species number	**14**	**15**	**7**	**7**	**9**	**10**	**7**	**10**	**9**	**9**	**9**	**10**	**1**	**10**	**2**
Slope angle (degree)	**15**	**20**	**30**	**30**	**40**	**30**	**75**	**30**	**40**	**50**	**40**	**45**	**50**	**35**	**70**

Transect 2

Site number	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Plant species														
Acinos alpinus														
Aconitum napellus														
Adenostyles glabra														
Alchemilla alpina	10					5		5						
Alchemilla vulgaris	x													
Androsace alpina														
Androsace helvetica									5	x				
Anthyllis vulneria				x										
Arabis alpina														
Arabis soyeri														
Arctosstaphylos alpina														
Asplenium trichomanes														
Aster bellidiastrum						x								
Agrostis alpina														
Bartsia alpina														
Bellis perennis														
Carduus defloratus														
Carex firma		x	x	20					x		x	10		
Carex humilis								x						
Carex ornithopada		10										x		
Carex parviflora														
Carex sempervirens		x	10	25	15				15					
Carlina acaulis														
Cerastium holosteoides														
Cirsium spinosissimum														
Cyclamen purpurascens														
Daphne striata							5	x	5			x		
Deschampsia cespitosa														
Draba aizoides														

Site number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Dryas octopetala													15	
Erica carnae				5	10		20	40	5			25		
Eriophorum scheuchzeri														
Festuca pumila						5					5			
Festuca rubra	20		x								x			
Galium odoratum						x		x						
Galium anysophillon				x		x								
Gentiana brachyphylla							x							
Gentiana verna									x					
Gentianella ciliata							x	5						
Gentiana clusii									5			x		
Geum montanum									x					
Globuaria nudicaulis														
Globularia cordifola						5	x							
Gnaphalium hoppeanum										x				
Helianthemum alpestre				x										
Hippocrepis comosa					x		5							
Homogyne alpina	x	x							x					
Hylocomium splendens													5	
Juniperus communnis ssp. alpina														
Leucobryium glaucum										5	5			5
Lotus corniculatus														
Mercurialis perennis	x													
Minuartia gerardii											5			
Minuartia sedoides														
Moehringia ciliata										5				
Myosotis alpestris				x										
Pedicularis rostratocapitata														
Picea abies	10	10												
Pinguicala alpina														
Pinus mugo	30	40	80											

Site number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Poa alpina									x	5				
Polygala amarella				x										
Polygala chamaebuxus							x							
Potentilla anserina				x		5		5						
Potentilla aurea						x								
Potentilla brauneana														
Persicaria vivipara									10	x				
Primula auricula												5		
Primula glutinosa														
Pritzelago alpina													5	
Pulsatilla vernalis	x													
Ranunculus alpestris										x	20			
Ranunculus montanum		x						x						
Rhododendron hirsutum	10													
Rosa pendulina														
Rubus spp.														
Rumex scutatus														
Salix retusa		10												
Salix serpillifolia										5	5	10		
Salix waldsteiniana														
Saxifraga aizoides													x	
Saxifraga androsacea														5
Saxifraga aphylla														10
Saxifraga paniculata														
Scabiosa lucida												x		
Sedum atratum													x	
Senecio doronicum						10								
Sesleria albicans		30	10		5	40	40	25	5			x		
Silene acaulis										20	5	30		
Soldanella alpina	x													
Sorbus chamaemespilus														
Taraxacum officinale						5					5			

Site number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Thlaspi rotundifolium												5		
Thymus Praecox							x					5		
Trifolium pratense														
Trisetum distichophyllum														
Trollis europaeus														
Tussilago farfara														
Urtica dioica														
Vaccinium vitis idaea														
Valeriana montana														
Veronica aphylla										x		5		
Veronica chamaedrys					x	x	x							
Veronica fruticans														
Viola biflora		x						5						
Xanthoria parietina														
Altitude (m)	**1737**	**1770**	**1793**	**1867**	**1909**	**1948**	**1989**	**2026**	**2061**	**2082**	**2116**	**2148**	**2180**	**2214**
Coverage (%)	**80**	**100**	**100**	**50**	**30**	**75**	**70**	**85**	**50**	**40**	**50**	**95**	**25**	**20**
Species number	**10**	**10**	**5**	**9**	**5**	**12**	**10**	**10**	**12**	**10**	**9**	**13**	**5**	**3**
Slope angle (degree)	**30**	**40**	**30**	**35**	**45**	**30**	**45**	**30**	**15**	**30**	**10**	**60**	**80**	**70**

Transect 3

Site number	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Plant species														
Acinos alpinus														
Aconitum napellus														
Adenostyles glabra														
Alchemilla alpina		5	x	5	10									
Alchemilla vulgaris														
Androsace alpina												5		
Androsace helvetica														
Anthyllis vulneria								x						
Arabis alpina											5			
Arabis soyeri									x					
Arctosstaphylos alpina								x						
Asplenium trichomanes														
Aster bellidiastrum									x					
Agrostis alpina			x							x	30			
Bartsia alpina										10				
Bellis perennis				x										
Carduus defloratus														
Carex firma	5	x			x					x	5	5		10
Carex humilis							x		x					
Carex ornithopada				5	5									
Carex parviflora														
Carex sempervirens	10		5							30				45
Carlina acaulis														
Cerastium holosteoides														
Cirsium spinosissimum														
Cyclamen purpurascens														
Daphne striata			x		x			x						
Deschampsia cespitosa														
Draba aizoides											x			
Dryas octopetala														

Site number	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Erica carnae	15	10				15	50	20						
Eriophorum scheuchzeri														
Festuca pumila		x		x				5					15	
Festuca rubra														
Galium odoratum				5	x									
Galium anysophillon							x							
Gentiana brachyphylla										10				
Gentiana verna					x		x						x	
Gentianella ciliata							5							
Gentiana clusii	x		x											
Geum montanum										x				
Globuaria nudicaulis								x						
Globularia cordifola									25					
Gnaphalium hoppeanum														x
Helianthemum alpestre										x				
Hippocrepis comosa														
Homogyne alpina	x	5												
Hylocomium splendens														
Juniperus communnis ssp. alpina	45					x								
Leucobryium glaucum									10		x	5		
Lotus corniculatus					5		x							
Mercurialis perennis														
Minuartia gerardii													10	
Minuartia sedoides														
Moehringia ciliata														
Myosotis alpestris										10				
Pedicularis rostratocapitata														
Picea abies														
Pinguicala alpina														
Pinus mugo		40	50	40	30	50	10							
Poa alpina				10		10	5							
Polygala amarella														

Site number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Polygala chamaebuxus		10												
Potentilla anserina							x							
Potentilla aurea														
Potentilla brauneana	x													
Persicaria vivipara														
Primula auricula										15				
Primula glutinosa														
Pritzelago alpina							x							
Pulsatilla vernalis														
Ranunculus alpestris			x		x									
Ranunculus montanum													x	
Rhododenderon hirsutum		x			5	x	x							
Rosa pendulina		x				10		10						
Rubus spp.		x												
Rumex scutatus														
Salix retusa														
Salix serpillifolia	5													
Salix waldsteiniana											10		15	
Saxifraga androsacea														
Saxifraga aphylla														
Saxifraga paniculata														
Scabiosa lucida												x		x
Senecio doronicum		x	5				10	x						
Sesleria albicans								10						
Silene acaulis	5	25	30	20	35	x	15		10		x			5
Soldanella alpina													30	20
Sorbus chamaemespilus	x		5			x								
Taraxacum officinale														
Thlaspi rotundifolium						x				10				
Thymus Praecox														
Trifolium pratense							5							
Trisetum distichophyllum										5				
Trollis europaeus														

Site number	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Tussilago farfara														
Urtica dioica														
Vaccinium vitis idaea														
Valeriana montana														
Valeriana saxatyllis				5				45			10			
Veronica aphylla													5	
Veronica chamaedrys		x					x				x			
Veronica fruticans														
Viola biflora		x		x										
Xanthoria parietina														
Altitude (m)	**1724**	**1752**	**1780**	**1815**	**1850**	**1885**	**1926**	**1968**	**2010**	**2049**	**2079**	**2116**	**2154**	**2200**
Coverage (%)	**85**	**95**	**90**	**85**	**95**	**85**	**100**	**90**	**45**	**95**	**70**	**15**	**75**	**80**
Species number	**10**	**12**	**10**	**9**	**11**	**9**	**15**	**10**	**6**	**11**	**10**	**4**	**7**	**6**
Slope angle (degree)	**30**	**35**	**30**	**30**	**40**	**40**	**40**	**40**	**50**	**10**	**60**	**70**	**60**	**30**

Appendix 2

Historic records from the beginning of the last century of the occurring plant species based on the works of Rübel (1911), Lüdi (1921) and Jenny-Lips (1933) (cited in Grabner 2000).

Krummholz - treeline area	Subalpine, alpine grassland	Seslerio - Caricetum sempervirentis 1900-2100 m	>2100 m	Scree vegetation	Snowbed vegetation
Acer pseudoplatanus	*Acinos alpinus*	*Alchemilla vulgaris*	*Alchemilla alpina*	*Achillea atrata*	*Arabis caerula*
Actaea spicata	*Anthyllis vulneraria*	*Briza media*	*Alchemilla vulgaris*	*Athamanta cretensis*	*Ranunculus alpestris*
Alnus alnobetula	*Carex sempervirens*	*Crepis aurea*	*Carex firma*	*Campanula cochlearifolia*	*Saxifraga androsacea*
Avenella flexuosa	*Daphne striata*	*Helianthemum grandiflorum*	*Carex mucronata*	*Cirsium spinosissimum*	*Saxifraga aphylla*
Campanula scheuchzeri	*Dryas octopetala*	*Potentilla aurea*	*Chamorchis alpina*	*Festuca pumila*	*Saxifraga stellaris*
Daphne striata	*Erica carnea*	*Potentilla erecta*	*Daphne striata*	*Linaria alpina*	
Dicranium scoparium	*Globularia cordifolia*		*Draba aizoides*	*Minuartia austriaca*	

Krummholz - treeline area	Subalpine, alpine grassland	Seslerio - Caricetum sempervirentis 1900-2100 m	>2100 m	Scree vegetation	Snowbed vegetation
Erica carnae	*Phyteuma orbiculare*		*Dryas octopetala*	*Moehringia ciliata*	
Geranium sylvaticum	*Polygala chamaebuxus*		*Erica carnea*	*Pritzelago alpina*	
Huperzia selago	*Scabiosa lucida*		*Globularia cordifolia*	*Rumex scutatus*	
Hylocomium splendens	*Senecio doronicum*		*Gnaphalium hoppeanum*	*Sedum atratum*	
Knautia maxima	*Sesleria albicans*		*Minuartia sedoides*	*Sesleria albicans*	
Larix decidua			*Pinguicula alpina*	*Silene vulgaris ssp. Glareosa*	
Luzula sylvatica			*Poa alpina*	*Thlaspi rotundifolium*	
Paris quadrifolia			*Polygala chamaebuxus*	*Trisetum dystichophyllum*	
Phyteuma orbiculare			*Potentilla aurea*	*Urtica dioica*	

Krummholz - treeline area	Subalpine, alpine grassland	Seslerio - Caricetum sempervirentis 1900-2100 m	>2100 m	Scree vegetation	Snowbed vegetation
Pinus mugo			*Potentilla brauneana*	*Valeriana montana*	
Pleurozium schreberi			*Ranunculus alpestris*		
Pyrula rotundifolia			*Salix retusa*		
Rhododenderom ferrugineum			*Saxifraga androsacea*		
Rhododenderom hirsutum			*Saxifraga caesia*		
Rhytidiadedelphus triquetrus			*Saxifraga moschata*		
Rosa pendulina			*Saxifraga oppositifolia*		
Rubus saxatilis			*Sesleria albicans*		
Salix appendiculata					

Krummholz - treeline area	**Subalpine, alpine grassland**	**Seslerio - Caricetum sempervirentis 1900-2100 m**	**>2100 m**	**Scree vegetation**	**Snowbed vegetation**
Sesleria albicans					
Sorbus aucuparia					
Sorbus chamaemespilus					
Vaccinium gaultherioides					
Vaccinium myrtillus					
Vaccinium vitis idaea					