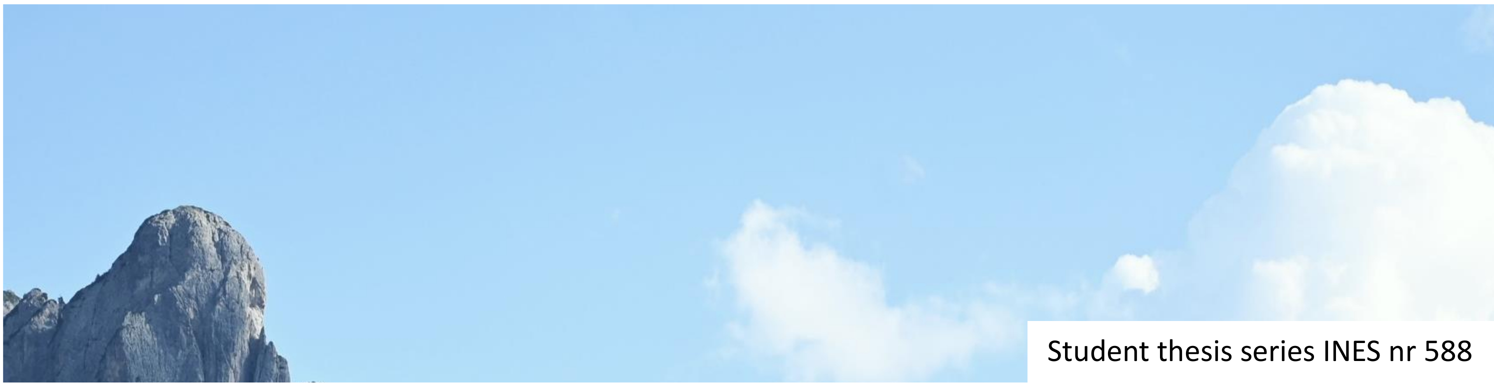

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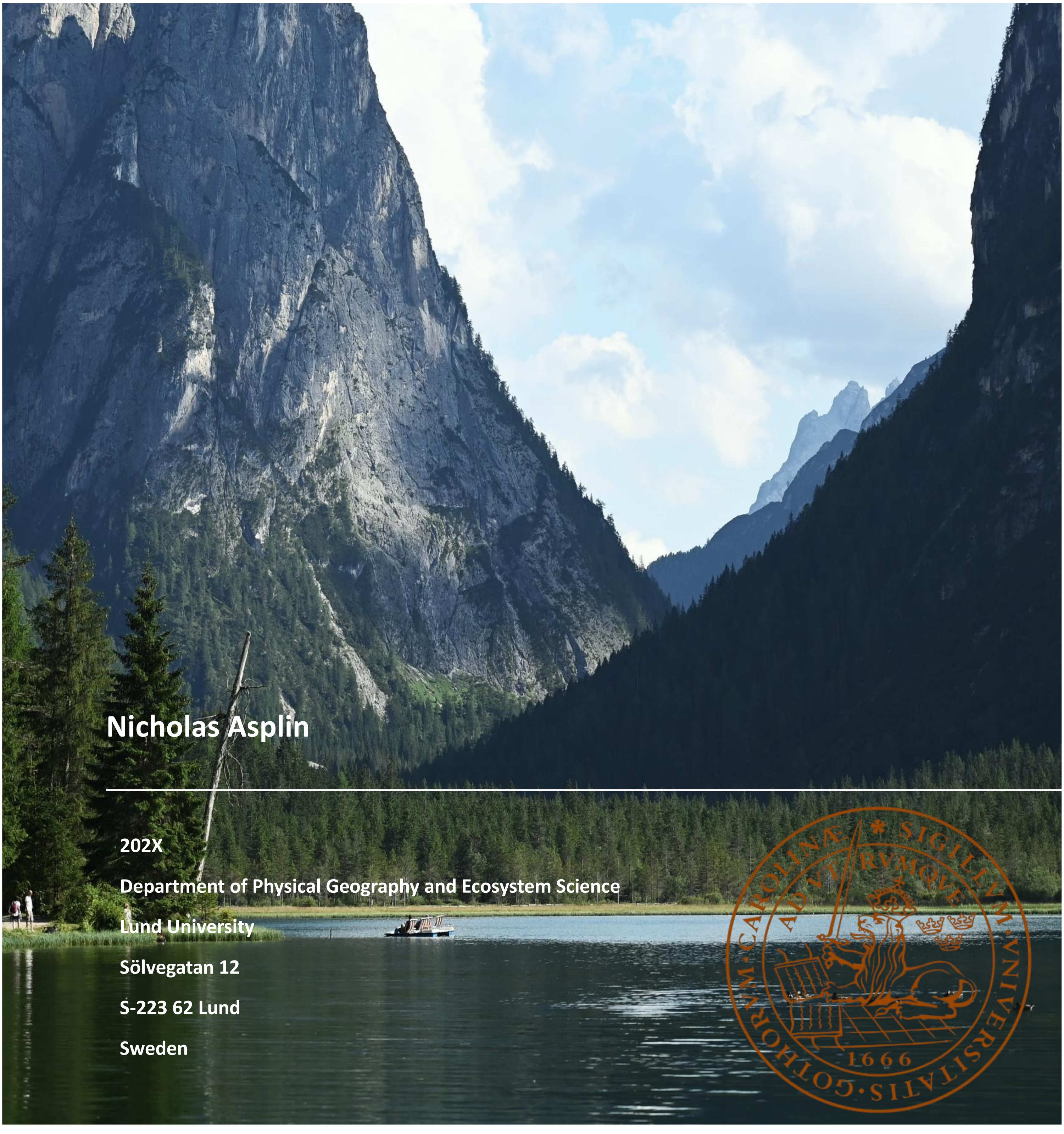
The Effects of Climate Change on Zirben (*Pinus cembra*) Distribution in the Italian Alps



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The Effects of Climate Change on Zirben (*Pinus cembra*) Distribution in the Italian Alps

Effekterna av Klimatförändringar på Cembratall (*Pinus cembra*) Fördelning i de Italienska Alperna

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Cover photo: The Toblacher See and the adjacent mountains in Süd Tirol. Photographer: Nicholas Asplin

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Abstract

Anthropogenic climate change has caused temperature increases all across the globe. Mountainous areas are among the most affected and are experiencing alarming rates of warming. Such rapid warming will have effects on alpine vegetation and their distribution throughout the alps. While there are many studies that have investigated shifting vegetation distribution around the world, none have found concrete evidence of an upwards shift of the tree line within the Alps to date. This study therefore investigates the potential size and timing of a tree line shift within the Martell Valley in the Italian Alps. Zirben (*Pinus cembra*) is a common tree species at the alpine tree line and is the focus of this investigation. Changes in average summer temperatures were the main factor investigated in this report as they were found to be the limiting factor for tree growth at the tree line. Average summer temperature differences were found between the current climate and for four different future climate scenarios: two for the near future and two for the far future. Differences in average summer temperatures between current (2011-2020) and future climates (RCP 4.5 & 8.5 2041-2060, RCP 4.5 & 8.5 2081-2100) ranged from 1°C to 7°C which corresponded to a potential upwards shift ranging between 194 and 794 meters. While these numbers indicate a potential shift, there are many factors that could delay a Zirben migration such as future climate uncertainties, alpine pasture usage, soil formation duration, seed dispersal and disturbance rate among other factors. In reality, the quantified shift values were concluded to be generalizations at best due to uncertainties in these factors. Future studies are recommended to physically study Zirben at the tree line for the next decades to a century to order to observe trends in tree line shift and Zirben migration.

Contents

1. Introduction

Since the beginning of the industrial era, anthropogenic activities have caused a rapid change in climate around the world (IPCC, 2023). This rapid change in climate has brought a host of secondary effects along with it such as increased extreme weather, sea level rise and vegetation shifts. Many environments are threatened by such changes, including mountainous environments which are among some of the most vulnerable (Walther et al., 2005).

The Alps, a mountain range in Central Europe, are experiencing a rapidly changing climate. Since the end of the 19th century, the Alps have warmed at double the rate compared to the rest of the Northern hemisphere (Auer et al., 2007). Precipitation has also been changing, although not as homogenously as temperature (Auer et al., 2007). The changes in temperature and precipitation have many consequences such as a lengthening snow-free period, increased mass movements and increased frequency of extreme weather (Gobiet et al., 2014). In addition to this, increasing temperatures are causing the thermal boundaries which limit vegetation growth to shift upwards. This then allows for an upwards shift of vegetation in the Alps, as species adapt to a new alpine climate (Pauli et al., 2003).

Tree lines, the altitudinal or latitudinal limit of tree growth, are thought to be efficient bioindicators of climate change induced temperature changes. This is due to tree growth at the tree line being temperature limited (Körner, 1998; Öberg, 2010). Researchers have found tree line shifts due to rising temperatures in other temperate mountain ranges (Kullman, 2002; Solly et al., 2017) and a shift in nival vegetation has also been observed in the Alps (Pauli et al., 2003). Currently, conclusive evidence of the tree line migrating upwards is yet to be found and continued research on the topic is necessary (Hättenschwiler & Körner, 1995).

Common high altitude tree species in the Alps include Norway Spruce (*Picea* abies), European Larch (*Larix* decidua) and Zirben (*Pinus cembra*). Zirben is a very prevalent tree species at the Alpine tree line and are one of the tree species for which climate change effects will be the most visible. This makes it a great focus for research conducted at the tree line (Grabherr et al., 2010; Hättenschwiler & Körner, 1995; Wieser et al., 2009) and is the reason why it is the focus of this report. Being the focus of this study, it is important to understand the behavior of a tree species under these changing climatic conditions.

An alpine plant, such as Zirben, under threat from a changing climate has three coping mechanisms at its disposal: (1) persist where it is during the new climate, (2) migrate to more favorable conditions or (3) die (Walther et al., 2005). Given the rapidly changing alpine climate and findings from previous studies concerning shifts in tree species' distribution ranges, coping mechanism number (2) seems a likely contender (Grabherr et al., 2010; Kullman, 2002; Solly et al., 2017; Vittoz et al., 2013; Wieser et al., 2009; Zimmermann & Bugmann, 2008) and will be investigated throughout this report. A shift in Zirben is synonymous with an overall shift in the tree line and a change in alpine vegetation composition in many parts of the Alps.

1.1. Aim

The aim of this report is to investigate the shift in the spatial ecological niche of Zirben in relation to climate change and to predict a new potential upper limit for future climate scenarios. This is done through a GIS analysis. The main questions to be answered are:

- How large of a shift could take place?
- When would this shift take place?

2. Background

2.1. Climate Change

2.1.1. Climate change around the world

Anthropogenic activities have caused approximately 0.8 to 1.2°C of global warming through the emission of greenhouse gases such as carbon dioxide, nitrous oxides, methane as well as other green house gases since the start of the industrial era (IPCC, 2023). Currently, global warming is occurring at around 0.1 to 0.3°C per decade. This increase in temperature has and will continue to increase occurrences of extreme weather events, droughts and sea level rise (IPCC, 2023). In addition to this, many plant, insect and animal species are predicted to lose parts of their geographic range as the climate changes. Shifts in ecosystems are also a consequence of climate change with tundra being an example of an environment particularly at risk of degradation or loss as plants more adapted to warmer climates migrate into tundra zones (IPCC, 2023).

2.1.2. Climate change in the Alps

Average temperatures in the Alps have been increasing at around twice the rate compared to the rest of the northern hemisphere and reached around 2°C average temperature increase by 2007 (Auer et al., 2007). Around 0.25°C warming per decade in the Alps is expected until 2050; 0.36°C warming per decade is expected hereafter until the end of the century (Gobiet et al., 2014). Changes in precipitation are also expected but are not as spatially homogenous as temperature, with the north-western part of the Alps predicted to become wetter and the south eastern part predicted to become drier (Auer et al., 2007). Such changes bring a range of secondary effects. The growing season at the timberline of the central Austrian Alps was 168 ± 12 days between 1972 and 1985 but had increased to 196 ± 23 days between 1994 and 2004 (Wieser et al., 2009). In addition to this, a large decrease of snow cover below 1500m is predicted as well as a 40-60% loss of snow cover for winters that are 4°C warmer on average in Switzerland (Gobiet et al., 2014). Further secondary effects of climate change in the Alps include an increase in the intensity of extreme precipitation, increased rock and ice fall due to glaciers melting and thawing permafrost, increase in extreme temperature and increased drought (Gobiet et al., 2014).

2.1.3. Consequences of warming temperatures on vegetation in the Alps

Climate change is impacting some plant species' ability to thrive. For example, lowland *Pinus sylvestris* in Switzerland is slowly being out competed by the deciduous species *Quercus pubescens* (Vittoz et al., 2013) due to increased drought as well as warming temperatures which promote parasitic development (Vittoz et al., 2013). Species growing at higher altitude, such as Norway spruce (*Picea abies*), may be partly replaced by species which are more adapted to warmer climates such as *Abies alba* or *Fagus sylvatica* under certain climate projections (Zimmermann & Bugmann, 2008). In addition to this, dry inner-alpine valleys may find it difficult to sustain forests in the future due to the summers being too warm and dry and the winters still too cold, leading to a more steppe-like environment (Zimmermann & Bugmann, 2008). An upwards migration of trees at the tree line will also likely reduce the area of alpine tundra and/or grassland.

2.1.4. RCP scenarios

Representative Concentration Pathways, or "RCPs", are climate scenarios which base future atmospheric CO_2 concentrations (and therefore future climate) on a combination of future economic, technological, demographic and political developments (SMHI, 2023). Each different RCP scenario is denoted by a number which represents the difference between incoming and outgoing solar radiation in W/m^2. There are four different scenarios: RCP 2.6, 4.5, 6 and 8.5. Each scenario describes a future up until 2100. RCP 2.6 corresponds to a future with stricter political climate policies, decreased use of oil, human population only increasing to 9 billion, decreasing emissions after 2020 and negative emissions by 2100 whereas RCP 8.5 corresponds to CO_2 emissions three times higher than current emissions and a strong increase in methane emissions, high energy usage, no future climate policies, a human population which increases to 12 billion and a strong dependency on fossil fuels. The other two scenarios (RCP 4.5 and 6) fall in between the aforementioned scenarios (SMHI, 2023).

2.2. Tree line

The tree line (sometimes called the forest line) ecotone encompasses the transition zone between the closed forest and the alpine vegetation zone and includes a few different zones within it as can be seen in figure 1. At the the lowest altitude of the tree line ecotone, the timberline is found. This is the boundary of the closed forest (Körner, 1998). At the highest altitude, the tree species limit is found. Although trees here are the same species as those below at the tree line, they often exist here as krummholz or trees with stunted growth which do not match the definition of a tree (a woody plant with a height above 3m (Körner, 1998)). The tree line is therefore found in the middle, at an altitude where the last trees which match the definition of a tree grow.

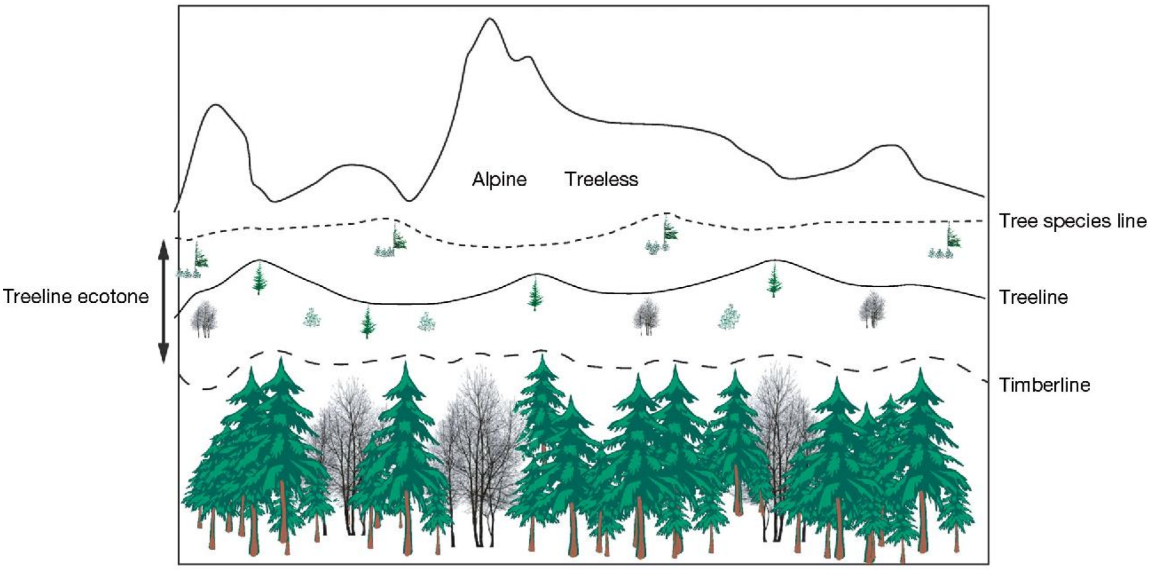

Figure 1. depiction of the tree line ecotone and its features. Taken from Wielgolaski et al. (2017)

Tree line is determined by temperature, specifically average summer temperatures (Körner, 1998). Körner (1998) found that a root zone temperature below the range of 5.5-7.5°C during the summer causes tissue growth to become negligible or cease, preventing trees from growing at higher altitudes and thereby forming the tree line. The soil temperature under trees in a closed canopy is coupled with the air temperature (Körner, 1998) indicating that air temperature can be used as a proxy for tree line threshold temperature. There are other factors which can influence the tree line position such as disturbances from rocks or snow, frost and seed establishment (Körner, 1998). These factors are said to be "modulatory", compared to average summer temperature, as they play a role in fine-tuning the tree line rather than dictating it (Körner, 1998). Other anthropogenic disturbance factors contribute to tree line position; grazing cattle, sheep and goats above the tree line has been a tradition in Europe for a long time and has artificially lowered the tree line in many parts of the Alps (Aubrey et al., 2023; Wielgolaski et al., 2017). More recently, tourism and recreation, for example construction and maintenance of ski resorts, have also artificially lowered the tree line throughout the Alps (Wielgolaski et al., 2017).

2.3. Zirben

Zirben (*Pinus cembra*), also known as Swiss stone pine or Arolla pine, is a tree species found at the tree line which grows in the range of 1000m to 2500m as well as in isolated cases up to 2700m. Zirben grows all across the Alps as well as in sections of the Tatra mountains, the Carpathians and the Transylvanian Alps. It is a slow-growing tree, usually reaching a height of 10-12 meters but occasionally growing as tall as 20-25m (C.A.B. International, 2002). It can take as long as 30 years for Zirben to reach 1.30m tall making it a poor competitor everywhere except in high alpine environments to which it is better adapted than other tree species (Ulber et al., 2004). Typically, Zirben grows in areas where the mean annual rainfall is between 800 and 2000mm and the mean annual temperature is between -2 and 7°C (C.A.B. International, 2002), although it is frost resistant down to -43°C. Its needles come in bunches of 5 and its seeds are found in cones which are spread by the Eurasian Nutcracker (*Nucifraga caryocatactes*) and a few other animals (Caudullo & De Rigo, 2016). Zirben used to be heavily cut for its wood, though today cutting it is strictly controlled (Aubrey et al., 2023). Its uses generally include light construction (e.g., beds), cultivation for pine nuts and handicrafts. Its cones are also used for the flavoring of alcoholic distillates, known as Zirbenschnaps (C.A.B. International, 2002).

2.4. Previous studies

Other researchers investigating general tree line shifts in other temperate mountain ranges such as in the Scandes (Kullman, 2002) and in the Urals (Solly et al, 2017) concluded that the tree line has shifted following changes in climate. In the Scandes, the treeline has shifted 150m upwards since 1950 and in the Urals a 35-80m shift has occurred since 1920, colonizing areas which were previously tundra. Research by Crepaz et al (2021) found that the mountain sedge *Carex humilis Leyss* had increased its maximum range elevation from 2150m a.s.l. in 1976 to 2371m a.s.l. in 2018 on a mountain side in Süd Tirol, Italy.

Research about shifts in Zirben distribution has not been as conclusive as findings in the other studies mentioned. A study by Hättenschwiler & Körner (1995) found that increased temperature had no effect on the recruitment of Zirben trees above its current range. Although, the study also concluded that "a time span of 10yr may be too short for observing changes in recruitment patterns" (p.11). This is backed up by findings from Szeicz & Macdonald (1995), who found that successful establishment of seedlings required summer temperatures to be optimal for up to 50 years after germination. Given that the study by Hättenschwiler & Körner (1995) was conducted nearly 30 years ago and that the climate in the Alps has continued to warm since then (Auer et al., 2007) and that temperature is the main controlling factor of the tree line (Körner, 2007), an upslope migration of Zirben's range is plausible and has also been predicted by other researchers (Grace et al., 2002; Holtmeier and Broll, 2007; Walther, 2003; cited in Wieser et al., 2009). One study found a Zirben seed germinating at above 3000 meters (Grabherr et al., 2010), 700 meters above the local timberline. This could be proof of the beginning of an upwards Zirben migration, however, nothing more about upwards migration was discussed in the paper and the Eurasian nutcracker is also known to spread seeds up to 700 meters vertically (Ulber et al., 2004).

2.5. Study area

The Alps are a mountain range in central Europe which are 1200km long and 250km wide at their widest point (Aubrey et al., 2023). They span through the countries of France, Switzerland, Italy, Liechtenstein, Austria, Germany and Slovenia and cover an area of 207,000 square kilometers. They reach 4809m a.s.l at their highest point of Mont Blanc, situated on the French-Italian border and descend to around 100 meters at their lowest point in the Adige valley in north eastern Italy (Aubrey et al., 2023). They are the source of many of Europe's largest rivers such as the Danube, the Rhine and the Rhone. Due to their elevation, the Alps have a significantly different climate to the surrounding areas, generally one that is cooler and wetter. They were formed around 65 million years ago during the alpine orogeny (Aubrey et al., 2023). Climate changes rapidly with elevation in the Alps which leads to many different vegetation zones. In the lower valleys, deciduous tree species such as Birch (*Betula pendula*), Beech (*Fagus sylvatica),* Oak (*Quercus robur*) or Elm (Ulmus) are common. At higher elevations, coniferous tree species such as spruce (*Picea* abies), Larch (*larix* Decidua) or Zirben (*Pinus* cembra) prevail (Aubrey et al., 2023).

Süd Tirol, also known as Alto Adige or South Tyrol, is an autonomous province in north eastern Italy which borders Austria to the north and Switzerland to the west. It has a population of around 535,000 (as of December 2021) and its capital city is Bozen/Bolzano (Suedtirol.info, 2020). The province covers an area of 7400km2; most of this area is very mountainous with 85.9% of the terrain existing at an elevation of 1000m or higher and 64.4% of its total area exists at elevations of 1500m or higher (Autonomous Province of South Tyrol Provincial Statistics Institute - ASTAT, 2020). The highest point in Süd Tirol is the Ortler, reaching 3905m a.s.l (Suedtirol.info, 2020). Climate in Süd Tirol is mainly dependent on elevation (Aubrey et al., 2023). Due to rapid changes in elevation, many different climate zones can be found in close proximity. According to the Köppen-Geiger classification scheme there are five climate types that can be found in Süd Tirol: Humid subtropical (Cfa), Oceanic (Cfb), Warm humid continental (Dfb), Subarctic (Dfc) and Tundra (ET) (Climate-Data.org, 2023) . Forest is the most dominant land cover type at 39.5%, followed closely by agriculture at 36.1 percent. Much of this forest exists in higher alpine areas with Zirben being a common species in the region.

This study focuses specifically on the Martell Valley which is a high alpine valley within the Stelvio National Park. The valley has 900 inhabitants, covers an area of 143km^2 and ranges in elevation from 800 to 3800m. The valley is mainly known for the national park, berries and biathlon (Gemeinde Martell, 2023). The valley was chosen as a location to focus on to show a potential Zirben shift due to the high presence of Zirben. Its location can be seen in figure 2 below.

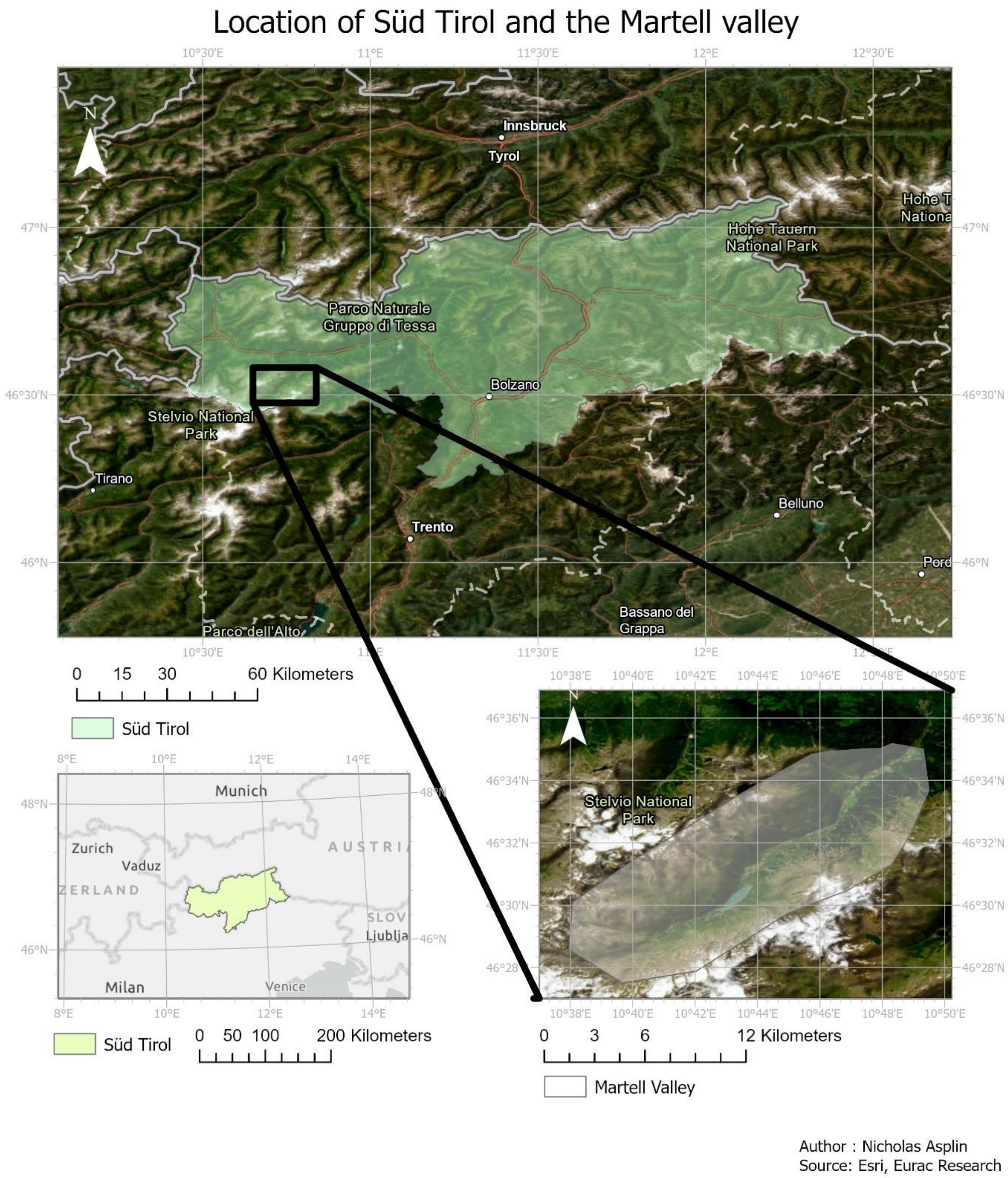

Figure 2. Location of Süd Tirol in relation to the rest of Europe and the location of the Martell Valley in Süd Tirol.

3. Method

To complete the analysis, the datasets that were required included forest location and type, a Digital Elevation Model (DEM), and temperature data containing both present and future scenarios.

To fulfill the aims, a GIS analysis was carried out where the forest data, climate data and a DEM were used in combination to predict a potential upper limit for the Zirben forest in future climates. Many other reports on this topic were also read to better understand tree line dynamics and to find climatic thresholds for Zirben growth which were used to aid the GIS analysis. All of the data analysis was done using ArcGIS Pro (ESRI Inc., 2020)

3.1. Input data

3.1.1. Temperature

Monthly average surface temperatures for year ranges 2011-2020, 2041-2060 and 2081-2100 from Debojyoti et al. (2020) were used (shown in table 1). Each temperature layer had a resolution of 1 km^2. RCP 4.5 and RCP 8.5 projections were used for future climates. The temperature data was then compiled into average summer temperatures (June, July, August) for each year range and scenario combination for the GIS analysis and was also compiled into annual temperature for the current scenario (2011-2020) to evaluate the data (see section 3.3).

Referred to in this paper as:	Current climate	Future Climates			
RCP scenario	N/A	RCP 4.5		RCP 8.5	
Year range	2011-2020	2041-2060	2081-2100	2041-2060	2081-2100

Table 1. Temperature datasets acquired from Debojyoti et al. (2020) for different year range and RCP scenario combinations.

A higher resolution monthly average temperature dataset for years 1981-2010 with a resolution of 250m^2 was used for the creation of more accurate isotherms (see figure 4) (Crespi et al., 2021). This data was loaded into ArcGIS as one averaged layer making it the average surface temperature for 1981-2010.

3.1.2. Forest data

Forest type data from 2011 for the Süd Tirol region was downloaded from the Süd Tirol Geocatalog (Autonome Provinz Bozen - Südtiroler Informatik AG, 2023). It contained a shapefile layer with 86 forest type classes in Süd Tirol, including four classes containing Zirben forests. Individual polygons represented unique forest stands.

3.1.3. Topography

A Digital Elevation Model (DEM) with a resolution of 10 meters was downloaded (Tarquini et al., 2023) for the eastern section of Süd Tirol, where the Martell Valley is located.

3.1.4. Administrative Boundary

An Administrative boundary shapefile was downloaded (Eurac Research, 2021). This shapefile was used solely for mapping purposes.

3.1.5. Land use

A land use map for Süd Tirol was downloaded (Eurac Research, 2001). It contained 6 different land use classes including forests, grasslands and bare rock.

3.2. GIS analysis

The difference in average summer temperature was the main focus of this analysis since it was found by Körner (1998) that summer temperatures are the limiting factor at the tree line. Firstly, average summer temperature in the area where the current Zirben forest exists was found for the current climate as well as for the future climates (using data from Debojyoti et al. (2020)). The difference in average summer temperature between the current climate and each future climate was subsequently calculated. These values, combined with isotherms created by data provided by Crespi et al. (2021) were used to estimate the shift in limiting temperature and therefore the shift in the potential range of Zirben itself. The isotherms were created with an interval of 0.5°C meaning that a change in average summer temperature of 1°C would lead to a perpendicular shift up of 2 isotherms. Polygons representing future forest extent were created by hand for each future climate. The isotherms were traced above the current Zirben forest according to the difference in summer temperature values for the future climate in question. A visualization of this method can be seen in figure 3. In addition to this, a layer containing control points was created with points being placed at the tree line 1 kilometer apart. With the DEM enabled, the data was queried at both the control points and the top of the predicted range for each future climate above the control point to find the elevation at each point. These values were then entered into Excel in order to find the average potential vertical shift of the Zirben range for each future climate. In total, 15 control points were used. An administrative boundary of Süd Tirol was also used for the GIS analysis.

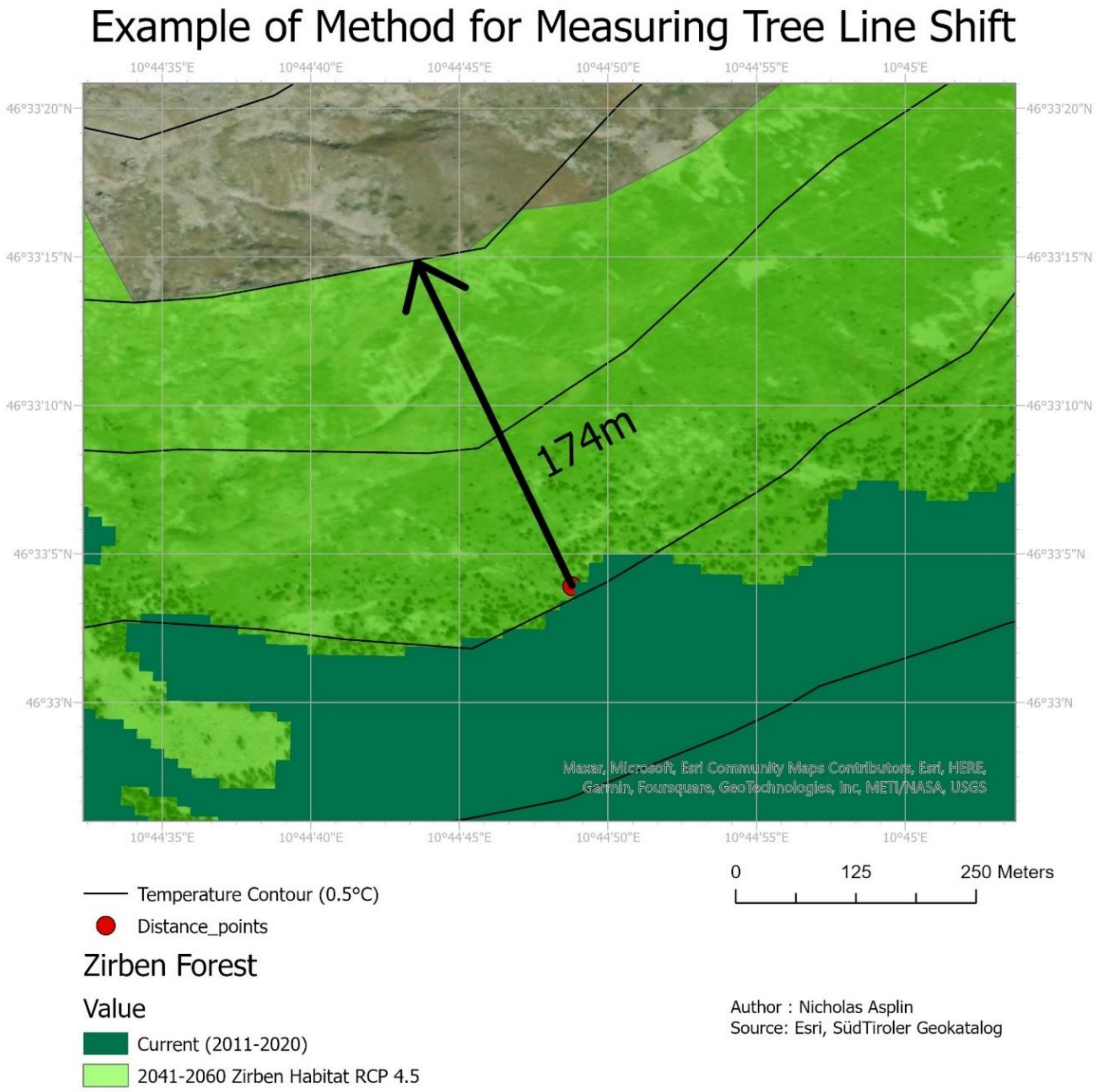

Figure 3. A visual example of how tree line shift was measured.

3.3. Data evaluation

In order to check if the temperature thresholds for Zirben found in literature matched the values found in the temperature dataset from Debojyoti et al., (2020) , current (2011-2020) annual temperature was found for Zirben forests across Süd Tirol. Zirben was found to exist between a temperature range of 6.94 and -1.73°C which corresponds closely to the values found in C.A.B. International, 2002 (-2 to 7°C) (p.50). Summer temperatures were also validated against literature. It was found that the coldest temperature in which Zirben exists during the current summers is 4.9°C which is a little colder than the 5.5-7.5°C range found in

Körner (1998). The lower limit of current summer temperatures within the Martell Valley were found to fall within the range found in Körner (1998) at 7°C.

3.4. Assumptions

Certain assumptions were made in order to fulfil the aims of this report. Implications of these assumptions on the results are discussed in section 5.2.4.

3.4.1. Forest data

Zirben was only found in mixed Zirben-Larch polygons and never in pure stands in the forest dataset. This was to be expected as Zirben is more often found in mixed stands than on its own (Caudullo & De Rigo, 2016). Zirben is usually the dominant species in a mixed forest with Larch (Caudullo & De Rigo, 2016). The assumption that it is indeed the dominant species in the mixed forest at the tree line was still made in order to use the data and fulfil the aims of this investigation. In addition to this, it is not known if the upper limit of the forest data occurred at the timberline or the tree line.

3.4.2. Temperature within the forest stand

In some sections of the average summer temperature layers, the grid cells (1km^2) would cover the entire vertical section of the forest stand meaning that these grid cells would not contain altitudinal differences in temperature within the stand section due to their resolution. The temperature found within the grid cell was assumed to be the temperature at the tree line, rather than anywhere lower in the stand.

3.4.3. Isotherms

Current climate data with a lower resolution of 1km^2 from Debojyoti et al., (2020) was deemed accurate enough to find the difference in average summer temperature of the Zirben forest between the current climate and future climates. However, when this current climate raster layer was turned into contours it was found that, while the data was of suitable accuracy in the lower valley where the Zirben forest exists, it was not suitable for the more sudden differences in topography that occur closer to the mountain peaks. For this reason, the higher resolution dataset (250m^2) from Crespi et al., (2021) was determined to be the better layer to turn into isotherms as they follow the topography (which is a central factor to determining temperature in mountainous environments (Aubrey et al., 2023)) of the mountain more accurately. The lower resolution data was used in conjunction with the higher resolution data, with the low resolution data being used to find values for the difference in future climates' average summer temperature and the high resolution data only being used to create isotherms.

It was assumed that any errors that would stem from using a temperature layer (and therefore isotherms) from a different dataset would be overshadowed by the gain in resolution. Polygons representing potential zirben shift would be able to more accurately follow the temperature gradient up the mountain by making this assumption. Figure 4 below illustrates the differences between the different resolution isotherms in high alpine areas of the Martell Valley.

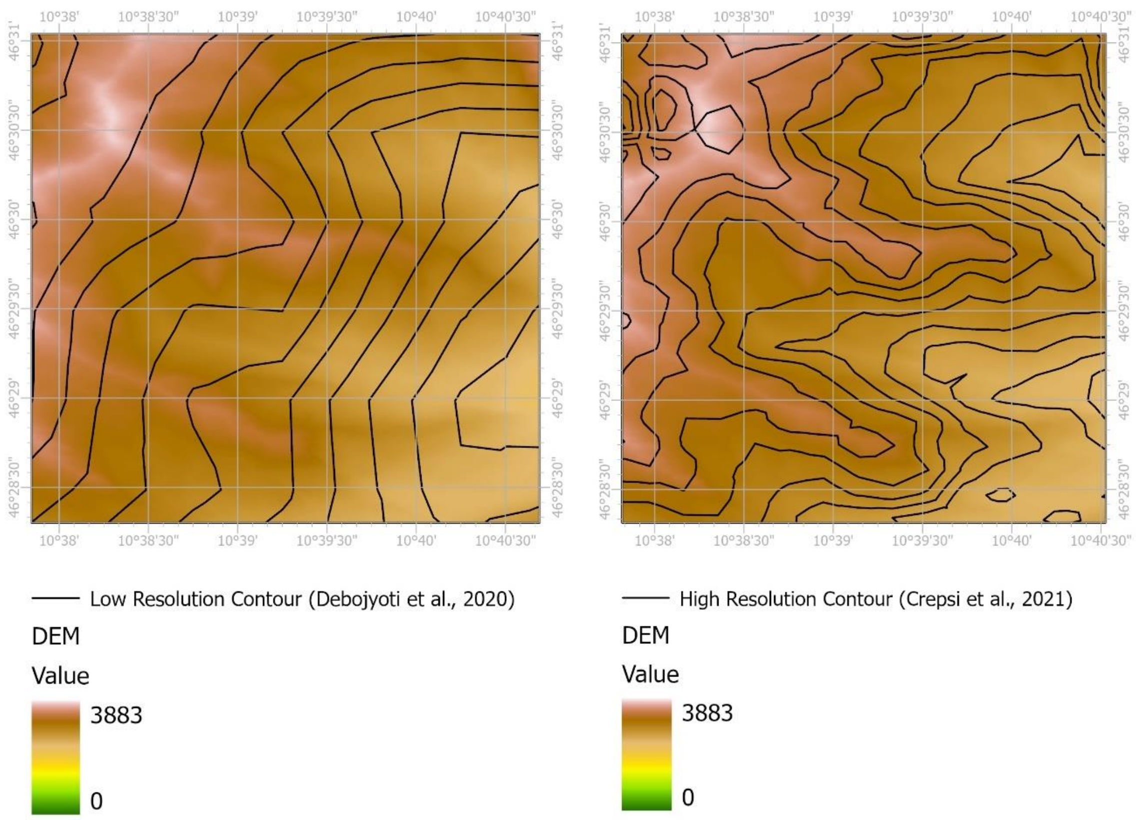

Figure 4. A comparison of isotherms created with high and low resolution datasets.

4. Results

2081-2100 projections yielded higher temperature increases for both RCP scenarios with temperatures being 3 and 3.5 times higher compared to the 2041-2060 year range for RCP 4.5 and RCP 8.5 respectively. Values in table 2 were rounded to the nearest half of a degree

Celsius as more accurate values could not be accurately accounted for during analysis. Table 2 depicts the average summer temperature differences within the Zirben forest between the current climate and future climate scenarios.

RCP scenario	4.5		8.5	
Year range	2041-2060	2081-2100	2041-2060	2081-2100
Difference in average summer temperatures (°C) between current and future climates (rounded to the nearest 0.5°C)	1.0	3.0	2.0	7.0

Table 2. Difference in average summer temperatures within the Zirben forest between the current climate and future climates.

In table 3 the average potential vertical shift of the tree line is shown. Similar to future temperatures, the shift is greater for the 2081-2100 year range in both RCP scenarios; for RCP 4.5, the potential vertical shift for the year range 2041-2060 is 194 meters, compared to 534 meters for the year range 2081-2100. Similarly, a large difference is also found in the RCP 8.5 scenarios between the years of 2041-2060 and 2081-2100, with a shift 354 meters and 794 respectively.

RCP scenario	4.5		8.5	
Year range	2041-2060	2081-2100	2041-2060	2081-2100
Average vertical shift in meters	194	534	354	794

Table 3. Average vertical shift in meters for each future climate.

In certain cases, potential shift in the Zirben forest would be limited by the topography of the mountain, for example, if it had reached the peak. Shifts that were limited by such topography and also fell outside one standard deviation from the mean were excluded from the average. This was due to one section of the valley where the height of the peaks was relatively low, limiting the potential vertical shift of the Zirben forest compared to adjacent mountains. Therefore, these numbers were not representative of the average shift and were excluded. Due to the size of the shift for the years 2081-2100 under the RCP 8.5 scenario, topography was a limiting factor for all values and therefore none were excluded.

The shape of the potential shift is largely determined by topography of the mountain. On certain sections of the map in figure 5 below, the shift looks much larger than in other sections. This is mainly due to that specific section of the mountain being flatter than adjecent sections, causing the shift to look larger on a 2D map.

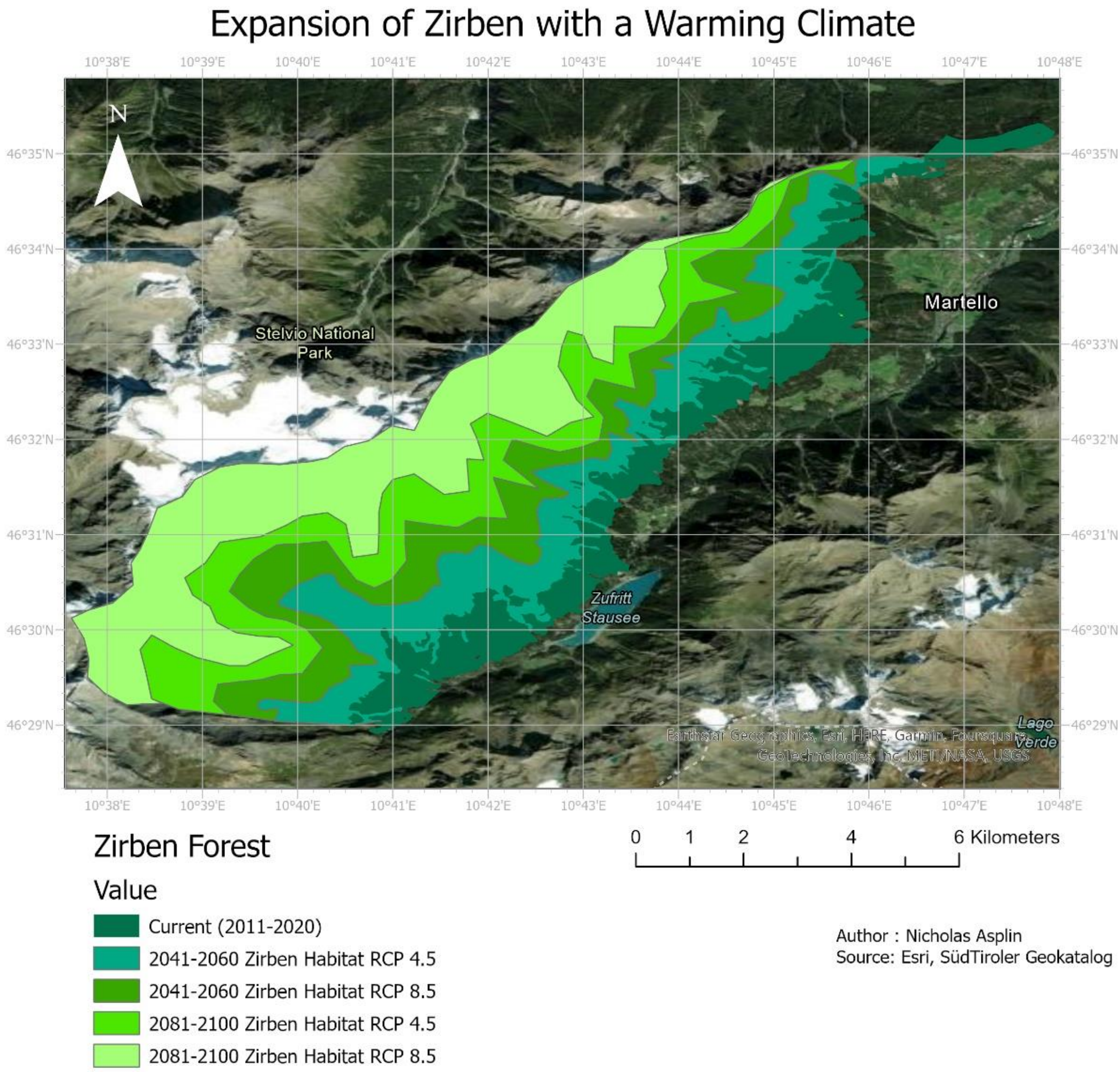

Figure 5. 2D visualization of the potential upper limit of the Zirben forest for each future climate.

A section of the 2D map is shown in 3D in figure 6 to aid visualisation.

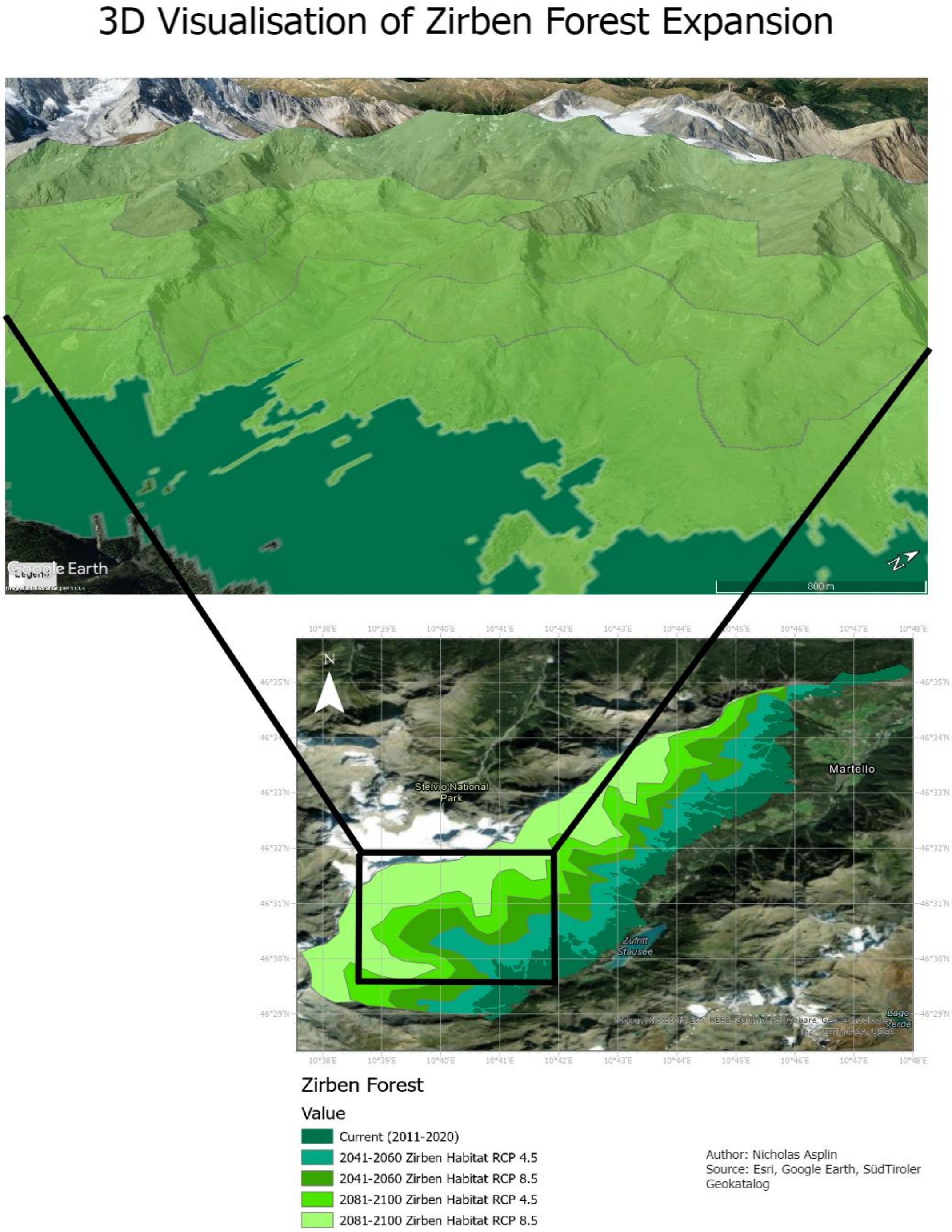

Figure 6. 3D visualization of a portion of figure 5.

5. Discussion

The rate at which any potential Zirben shift could occur is uncertain, hence why the shift is referred to as potential (i.e., the upper limit which *could* occur during the given time frame and scenario) rather than actual. According to past research, recruitment at the tree line (and thereby tree line shift) is episodic rather than gradual (Walther et al., 2005). This means that the position of the tree line undergoes periods of stasis where, despite a change in climate, the tree line does not shift and only enters periods of rapid change thereafter. In addition to this, Szeicz & Macdonald (1995) found that summer temperature has to be optimal for up to 50 years after germination for successful seedling establishment, making estimating a time frame for a Zirben shift difficult due to an unknown future climate. In a warming climate, it is more likely that summer temperatures will be optimal compared to previous decades. Both Hättenschwiler & Körner (1995) and Gehrig-Fasel et al., (2007) encountered these phenomena when researching tree line shifts in the Alps due to warming temperatures over a 10 and 12 year period respectively. Both papers concluded that their study period was likely too short to witness any shifts in the tree line. Over a smaller time frame such as a few years to a decade, the response to a change in climate occurs as increasing tree coverage, rather than a shifting tree line (Gehrig-Fasel et al., 2007). It is only in the longer term of a few decades to hundreds of years that response to climate change would occur as a tree line shift (Gehrig-Fasel et al., 2007). This large range for response time, coupled with the up to 50 years of optimal conditions needed after germination for establishment, makes any estimates for when a Zirben shift would occur very uncertain. Several biotic and abiotic factors can affect the extent and timing of the actual shift.

5.1. Factors affecting the rate and size of a potential shift

5.1.1. Seed dispersal

The Eurasian Nutcracker's (*Nucifraga caryocatactes*) ability to also adapt to a changing climate will directly affect whether or not Zirben could shift upslope. The Eurasian Nutcracker is not currently endangered, however, it is classified as a species with a high vulnerability in the Alps (Maggini et al., 2014) meaning that it will likely become endangered in the future. With warming temperatures, the Eurasian Nutcracker is expected to migrate to higher elevations which would seriously reduce their distribution area in the Alps or even lead to their disappearance altogether (Maggini et al., 2014). The reduction or loss of

Zirben’s primary seed disperser could greatly reduce Zirben’s ability to shift as seeds would stay locked within the cones, unable to germinate (Ulber et al., 2004). There are a few other animal species which can open Zirben cones and spread the seeds (Caudullo & De Rigo, 2016) so seed distribution would not be completely halted in the absence of the Eurasian Nutcracker but would likely be greatly reduced. The uncertainty of the Eurasian Nutcracker’s future translates to uncertainty in the size and rate of a potential shift.

5.1.2. Geomorphology

When looking at nival vegetation shifts in the Alps, Pauli et al. (2003) found that “the rate of upward movement was highly related to the geomorphological shape of mountain summit areas” (p.2) and that peak areas with structured ridges had a much increased species richness compared to peak areas with lots of unstable scree due to a lower disturbance rate. While the physical structure of nival vegetation and Zirben trees are quite different, geomorphology is also important for the distribution of alpine trees (Maggini et al., 2014). Even though Zirben is known to be able to establish itself on rocky surfaces (Ulber et al., 2004), it would likely not be able to survive in a higher disturbance environment such as scree (Körner, 2007) indicating that the conclusions drawn in Pauli et al. (2003) about how nival vegetation shifts upwards likely would apply to a Zirben shift as well.

5.1.3. Lengthened growing season

Growing season in the Alps has already been increasing in the last few decades (Wieser et al., 2009). In the current climate, a longer growing season would be beneficial for Zirben and could potentially increase the rate of an upwards shift (Gao et al., 2022). However, in a potentially drier future climate a longer growing season would not affect or even be disadvantageous for Zirben. A study on alpine plants in a dry environment determined that due to a longer growing season, plants gain more biomass in the spring but then lose more in the late summer/autumn due to increased water stress (Wang et al., 2020). Depending on how precipitation changes in the future, a longer growing season could either enhance or reduce Zirben’s ability to shift.

5.1.4. Soil formation

For Zirben to successfully shift upslope, it will require optimal soil conditions in addition to optimal climate conditions. Zirben grows optimally in podzolic soils (C.A.B. International, 2002). A study conducted in Val Genova, 35km south of the Martell Valley, found that Podzols require at least 1200 years to form at high altitude after deglaciation (Egli et al., 2003). It has been around 11,500 years since the end of the last ice age (Bennike, 1999) and glaciers did not expand significantly during the Little Ice Age in the Martell Valley (Knoll et al., 2009) so podzols theoretically would have had enough time to form. However, there are factors which limit soil formation in mountainous areas more than the presence of obstructions such as glaciers. Currently, soil conditions in high alpine areas do not meet the requirements for Zirben growth. Low temperatures limit biological activities and therefore evolution of soil, and steep slopes allows for easier erosion of relatively nutrient-rich top soils (FAO, 2015). These factors which limit soil formation could potentially limit an upslope Zirben migration as the trees would likely need at least some soil to establish themselves as a closed forest. Soil formation also brings more uncertainty to when a Zirben shift could take place as it is not known when or if soils would form at higher altitudes. Soil would likely only begin to limit a potential Zirben shift when Zirben would start to shift into high alpine areas where there is currently no soil. However, it could also be that by the time a vertical shift this large were to occur some soil would have already formed, especially if the climate in high alpine areas is much warmer than it is today.

Figure 7 shows the location of Alpine grassland located above the tree line in the Martell Valley. The location of grassland could serve as a proxy for the location of soils on the mountain side and provide an estimation to where Zirben would shift to first. As can be seen in figure 7, all the area above the tree line that is not grassland is classified as bare rock. Zirben migration into this area would likely take longer than into the grassland area since soil would need to form first. An increase in temperature could potentially speed up chemical reactions (Egli et al., 2006) leading to faster soil formation in the future and therefore a faster potential shift into areas currently classified as bare rock.

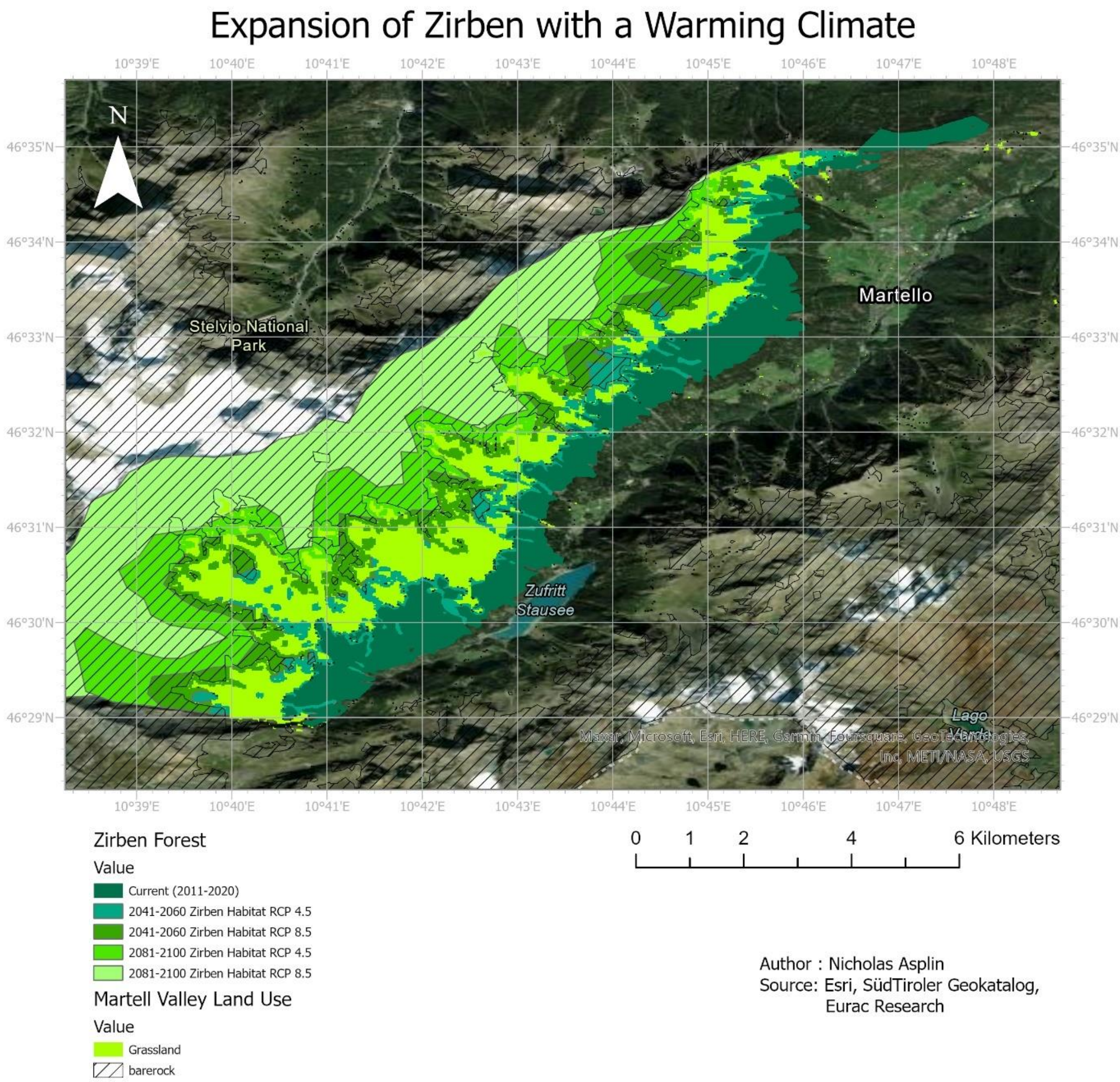

Figure 7. Grassland and bare rock land use classes overlaid on the map showing the potential upper limit of the Zirben forest for each future climate.

5.1.5. Abiotic Disturbances

In a future climate with higher temperatures and more intense precipitation, a higher disturbance rate can be expected. Disturbances such as landslides are a threat to Alpine plants attempting to establish themselves at the tree line (Körner, 2007). Warming temperatures have caused permafrost in the Alps to thaw causing alpine slopes to become increasingly unstable and increasing landslide frequency (Gobiet et al., 2014). Increased extreme precipitation has had a similar effect (Gobiet et al., 2014). Increased landslide occurrences could affect seedling's ability to establish themselves at or above the tree line. In addition to this, increased landslide occurrences could negatively affect soil formation, further reducing a potential upwards Zirben shift.

Disturbances such as high wind speeds are more common at mountain peaks than other places on the mountain and often prevent trees from growing in these locations (Körner, 2007). In the RCP 8.5 scenario for the year range 2081-2100, the potential tree line is predicted to move all the way to the top of the mountain. Zirben trees migrating to this level of the mountain would likely not occur due to the high disturbance rate found there (Körner, 2007). Zirben could potentially exist at such high altitudes if it could establish itself in an area sheltered from disturbances such as high wind or landslides, however, a closed forest area existing in such exposed high-altitude areas would be unlikely.

Forest fires could potentially become more of a threat in the Alps in the future due to rising temperatures. A study by Wastl et al. (2012) concluded that in the western and southern Alps, forest fires were increasing. However, the study also concluded that in the inner Alps, where Süd Tirol is located, results were inconclusive with trends varying from station to station. For now, it appears that forest fire risk is not greater than it was in the past, however, in a future climate forest fires have the potential to become more prevalent. Fire would pose a challenge to a potential Zirben shift by removing trees at the tree line and destroying seeds that otherwise would have been dispersed. It also increases tree's susceptibility to landslides and other mass movement events (Arpaci et al., 2014). As it stands, however, forest fires are likely a less important factor which could limit a potential Zirben shift.

One consequence of climate change is the increasing occurrence of extreme temperatures (Gobiet et al., 2014) rather than a more stable increase in average temperature. Heat waves are known to decrease tree growth in forest in the Alps (Pichler & Oberhuber, 2007). An increase in heat waves would likely reduce the rate at which Zirben could shift due to reduced growth speeds.

5.1.6. Biotic disturbances

Zirben is relatively unaffected by pests. There are a few species of snow mold fungi which can lead to the death of saplings if there is a deep cover of snow lasting into late winter or spring. There is also a species of moth which is known to defoliate Zirben, however, outbreaks are sporadic and do not influence the tree mortality rates. In a warming climate with shorter periods of snow cover, it is likely that instances of snow mold fungi affecting

Zirben saplings will decrease. This may have a beneficial effect for saplings at the tree line as with one disturbance less, survival and establishment chances may increase, potentially leading to a faster upwards Zirben shift.

Increased competition from other tree species could affect a potential Zirben shift. In the Swiss Alps it is expected that trees growing in the lower valleys will begin to migrate upwards and outcompete trees at higher elevations as the climate at higher elevations becomes more like the previous climate in the valley (Vittoz et al., 2013). Zirben currently faces very little competition from other tree species since not many other tree species can withstand the harsh climate at the altitude where Zirben grows (Ulber et al., 2004). Norway Spruce forests are often located at lower altitudes right below Zirben forests, unable to grow higher due to the colder conditions above which it cannot withstand. A warming climate may give Spruce the competitive upper hand at its own current tree line, allowing it to migrate upwards and outcompete Zirben at the lower edge of the Zirben forest. This is thought to have happened after the end of the last ice age where spruce outcompeted the Zirben tree at lower alpine valleys, forcing it to migrate to the high alpine areas where it currently can be found (Caudullo & De Rigo, 2016). Increased competition from spruce would have implications for predicting the total size of a potential Zirben shift since the Zirben forest might disappear from below while it shifts upwards, potentially leading to a net zero territory gain.

5.1.7. Anthropogenic disturbances

The largest anthropogenic disturbance at the tree line is cattle grazing. High Alpine farming has been taking place in the Alps for millennia with the first high alpine forest clearing for pastures dating back to 4000BC (Kral, 1993, cited in Gilck & Poschlod, 2019). In the eastern Alps, where Süd Tirol is located, pollen analyses revealed that the first human impact at higher altitudes could be traced back to 2500 BC (Gilck & Poschlod, 2019). Over millennia, the clearing of forests to make way for pastures has artificially lowered the tree line below its potential climatic maximum (Gilck & Poschlod, 2019). The Martell Valley is known to have Alpine pastures (Premstlahof, n.d.), so it is likely that the tree line has also been artificially lowered here. This could have influenced quantitative shift results (table 3) as well as the map in figure 5 as it would have created a false started point for the analysis which was conducted. Continued Alpine pasture use could seriously hinder any potential Zirben shift as trees attempting to establish themselves would be removed to make way for pastures. A potential

Zirben shift could occur in patches, where areas in the valley which are relatively unaffected by grazing see an upwards shift but areas heavily grazed upon do not see an upwards shift. There is evidence that forest area has increased in other parts of the alps due to a decline in alpine farming (Gehrig-Fasel et al., 2007) which could mean that pastures would not pose as much of a threat to a potential Zirben shift if this is the case in the Martell Valley as well.

The presence of ski resorts can also artificially reduce the tree line as parts of the forest are cleared to make way for ski slopes (Rixen & Rolando, 2013). Currently, there are no ski resorts in the Martell Valley so there is no artificial lowering of the tree line due to this. However, in other parts of the alps this could be a central factor affecting current tree line position and Zirben's ability to shift.

5.2. Uncertainties

5.2.1. Uncertainty in Zirben's limiting climatic factor

A study conducted across the French Alps on the climate/growth relationship of high altitude Zirben concluded that Zirben growth in the southern French Alps is particularly influenced by winter precipitation instead of summer temperature due to the Mediterranean-influenced dry summers and the water stress associated with it (Saulnier et al., 2011). In the last few decades, winter precipitation has also had increasing influence on Zirben growth in the wetter northern section of the French Alps as a method to reduce water stress during the growing season (Saulnier et al., 2011). This does not necessarily identify precipitation as a more limiting factor than temperature in the northern section of the French Alps at the moment. Rising temperatures in the French Alps have been causing water stress due to a reduction in snow cover and duration (Saulnier et al., 2011), reducing water availability during summer months. Along with experiencing an increase in temperature, Süd Tirol is expected to become drier, especially during the summer (Solomon et al., 2007). This creates uncertainty to the limiting factors of Zirben in the future, as the 5.5-7.5°C limiting summer temperature (Körner, 1998) may not apply in a future climate where precipitation becomes the bottleneck for Zirben growth. It is not known how changes in precipitation would affect Zirben migration at the tree line but it is unlikely that a decrease in precipitation during the growth season would aid seedling germination or establishment.

5.2.2. Data uncertainties

Debojyoti et al., (2020) evaluated their climate data against climate data obtained from the European Climate Assessment (ECA), which collects data from 4637 weather stations. For average summer temperature for the current scenario, the R^2 value was 0.90 when compared to data from the ECA. This implies that the climate model reflects actual recorded temperatures very accurately for the current scenario. For future scenarios, however, there are large uncertainties in model projections of climate, stemming from natural variability in climate, assumptions on future greenhouse gas emissions as well as errors and/or simplifications of the regional climate models used (Gobiet et al., 2014) meaning that potential Zirben shift values obtained for future climates (table 3) likely have some errors due to the data used. The average upwards shift of Zirben per degree was 166 meters. Even a slight difference in actual future average summer temperature, for example 0.5°C, would lead to the potential shift being around 88 meters higher or lower than the values given in the results. This is quite a substantial difference and highlights the need for future climate models to be accurate.

Data evaluation for the temperature only took place in Süd Tirol. The average summer temperature lower limit fell slightly outside of the value range found in Körner (1998) when evaluating the data in all of Süd Tirol but fell within this range when looking at the Martell Valley. Average annual temperatures fell within values found in C.A.B. International (2002). Due to this, the data was deemed to be reliable. However, it is possible that in Zirben forests outside of Süd Tirol the data deviate further from the literature values.

5.2.3. Human error

The polygons representing potential Zirben range shift were created manually and were based on visual estimation rather than being calculated. This was done due to the complexity of the tree line, however, it likely lead to some incorrect values when quantifying the shift. Estimating where to draw the polygons in areas where the surface of the mountain curved suddenly also proved challenging as it was difficult to trace the shape of the tree line below and follow the isotherms up perpendicularly when the isotherms were also very curved. The tree line is not a perfectly straight entity either; it has many sudden rises, dips and gaps in between. Choosing which irregularities to take into account and which ones to discard when creating the polygons was also a source of error as it was left entirely to visual estimation.

In addition to this, values obtained from finding the difference in average summer temperatures between current and future climates (table 2) were rounded to the nearest 0.5°C. None of the values were more than 0.2°C from the nearest 0.5°C. When tracing the isotherms to make the potential Zirben shift polygons, it was thought that accounting for such small differences in temperature would be difficult due to the polygons being formed by visual estimation. This likely affected the quantitative results for the Zirben shift, however, it is possible that creating the polygons by visual assessment introduces larger errors than not accounting for a couple tenths of a degree. Overall, human error is likely less important than other errors such as data errors, since these errors affect the size of the potential shift before any human error comes into play.

5.2.4. Errors from assumptions

Control points

When attempting to quantify the vertical size of the potential shift, 15 control points at a 1km distance from eachother were used. 15 was deemed a large enough sample size to obtain representative results, although, it is possible that using a larger sample size would have yielded slightly different results.

Forest data

As mentioned in section 3.4.1., Zirben is usually the dominant species in a mixed forest with Larch. Due to this fact, making the assumption that Zirben was always present at the tree line was likely a safe assumption to make. However, without evaluating high resolution satellite imagery or physically walking along the length of the tree line it cannot be stated with 100% certainty that Zirben was always present at the tree line. This could have affected the analysis as Larch could react differently to a changing climate, possibly making shift predictions inaccurate in areas that could have been Larch-dominant. In addition to this, the uncertainty to where the upper limit of the forest occurred in the data set (either at the timber line or the tree line) also could have affected the results by making upper limits in figure 5 systematically lower than they should have been. Accuracy of quantitative shift results (table 3) could be affected if distances between the timber line and tree line change in the future.

Temperature within the forest stand

During the GIS analysis, it was assumed that the Zirben growing at the tree line was at its current climatic maximum. An artificially lowered tree line may have affected the analysis by providing a false starting point when tracing the isotherms above the current Zirben forest. This could have caused the predicted potential shift to be lower than it might actually be. It was also assumed that the average summer temperature found within the Zirben forest layer was the temperature at the tree line despite the grid cells ($1km^2$) covering the whole vertical section of the tree line. At the Zirben forest stand's widest vertical point there is over 300m of altitudinal difference between the top and bottom of the stand which is large enough for a small difference in average summer temperature. As stated in section 5.2.1., even a small difference in temperature is enough to change the size of the potential shift by a substantial amount.

Isotherms

The use of separate temperature data to create isotherms from the temperature data which was used to find the difference in average summer temperature between current and future climates could have caused some errors. These errors could include discrepencies in physical distance between isotherms from the two different temperature layers due to seasonal and temporal differences of the data (data from Crespi et al., (2021) was the average temperature for 30 years whereas data from Debojyoti et al., (2020) was the average summer temperature over the course of 10 years). These discrepencies could have altered the potential Zirben shift distances measured for each future climate, however, as mentioned in section 3.4.3., the error in predicting potential Zirben shifts likely would have been greater if isotherms from the lower resolution data set from Debojyoti et al., (2020) was used to create isotherms.

5.3. Future study recommendations

Future studies are recommended to conduct studies over a period of more than 50 years in order to potentially witness establishment above the tree line and measure a shift in tree line. In addition to this, conducting a longer study would likely allow for more accurate predictions in tree line/Zirben shift. It is also recommended that studies take place in locations where there have been no disturbances from grazing in a long time so that it can be made certain that the expansion at the tree line is due to climatic reasons instead of a rebound into an abandoned pasture. Future studies are recommended to conduct further investigations on the effects of precipitation on Zirben growth as precipitation may become the limiting factor for Zirben growth in some parts of the Alps in the future.

6. Conclusion

According to the future climate data used, the thermal boundaries which currently limit Zirben from shifting upslope will shift to higher altitudes, theoretically allowing for an upslope Zirben shift. By tracing the shifting thermal boundaries above the tree line and calculating differences in upper limits of the current and projected forest, the potential shift of Zirben was quantified. While this technically achieved the first aim of discovering how large a potential shift could be, in reality, uncertainties in future climate as well as other factors such as soil formation, alpine pastures and seed germination/dispersal make the numbers presented in table 3 generalizations at best. The aforementioned limiting factors also translate to uncertainties in when a Zirben shift could or would occur, making the second aim of discovering when a potential shift could occur difficult to achieve. There will likely be a considerable time lag between a warming climate and a Zirben shift; it may be more than 50 years before any Zirben growth above the tree line occurs. Soil formation at high altitudes could take centuries which could severely limit the extent of a shift in the near future and the presence of alpine pastures has the potential to completely stop an upwards shift from occurring altogether. Even if Zirben managed to overcome these obstacles in the future, the steep slopes and high disturbance rate of the highest alpine areas likely will stop Zirben from shifting to areas as high as predicted in the 2081-2100 year range for the RCP 8.5 scenario. An upwards Zirben shift of any size will have ecological consequences such as changing the vegetation cover and biodiversity in high alpine areas. This study could be improved upon through continuous physical monitoring of climate and Zirben growth at Zirben forest upper limits over the course of many decades to a century. Investigations should also be conducted across the alps as factors which could affect Zirben in one location, for example the Martell Valley, might not apply to Zirben in other locations in the Alps.

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