PUBLIZIERBARER ENDBERICHT – FINAL REPORT

A) Project Data

Short title:	ClimInterVal
Full title:	Using forest growth data from the Austrian Central Alps to validate a climate interpolation model
Program:	ACRP, 4th Call for Proposals
Duration:	01.05.2012 – 31.01.2016 (45 months)
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Key words:	Climate change, weather data, spatial interpolation, forest growth, climate proxy data, validation, growth variation
Project costs:	453.252,00 €
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B) Project overview

1 Kurzfassung

(max. 2 Seiten, Sprache Deutsch)
Kurze Darstellung des Projekts, Zusammenfassung der wesentlichen Projektergebnisse qualitativ und quantitativ (bei Szenarien, Kostenanalysen, volkswirtschaftlichen Studien, Potenzialstudien sind ausgewählte nummerischen Werte festzuhalten – in % sowie die Werte selbst).

Gebirgswälder können aufgrund der Seehöhe, den bereits herrschenden extremen Wetterverhältnissen und exponierten Lagen sehr stark vom Klimawandel betroffen sein.Um die Auswirkung vom Klimawandel auf Gebirgswälder zu untersuchen sind daher Klimamodelle, die auch kleinräumige Unterschiede in Topographie und Seehöhe berücksichtigen, notwendig. Eine bereits angewandte Methode zu Berücksichtigung von kleinräumigen Verhältnissen in Klimamodellen, ist die Validierung von Klimainterpolationsmodellen auf Basis von gemessenen Daten von Wetterstationen und deren Interpolation. Allerdings, ist die Anzahl an Wetterstationen im Gebirge zu gering und zu weit auseinander um kleinräumige Unterschiede zu berücksichtigen.

In diesem Projekt wird, auf Grund dieses Problems, ein Klimainterpolationsmodell erstellt der die kleinräumige Unterschiede berücksichtigen soll. Es ist bekannt, dass die Jahrringbreite von Bäumen neben dem Standort und Konkurrenz auch von klimatischen Verhältnissen beeinflusst wird. Anhand von Jahrringen kann daher das vergangene Klima rekonstruiert werden (Dendroklimatologie).Ziel dieses Projekts ist Jahrringmessungen (Früh- und Spätholzbreiten) als Proxy-Daten für das vergangene Klima zu verwenden und zu überprüfen ob ein Klimainterpolationsmodel damit validiert werden kann.

Zur Datengewinnung wurden Bäume in 4 verschiedenen Gebieten in Tirol (Schlegeisspeicher, Durlaßboden und zwei benachbarten Seitentäler), die sich hinsichtlich ihrer Standortsmerkmale unterscheiden, beprobt. Dabei berücksichtigt wurden Seehöhe, Exposition, Bodenverhältnisse, Wasserhaushalt und soziale Stellung des Baumes. Bei den untersuchten Baumarten handelt es sich um die Fichte (*Picea abies*) und der Zirbe (*Pinus cembra*). Beide Arten sind typische Gebirgsbaumarten, wobei die Zirbe in höheren Lagen als die Fichte vorkommt.

Insgesamt wurden 24 Höhentransekte ab einer Seehöhe von 1300 m ü.N.N. bis ca. 2050 m und damit nahe der Baumgrenze angelegt und entlang dieser jeweils in regelmäßigen Abständen Winkelzählproben durchgeführt. Zudem wurden, verteilt im Untersuchungsgebiet, 56 Dendrometer installiert die stündlich über die ganze Projektdauer Änderungen am Baumumfang und Temperatur messen. Um die Bodentemperatur an den mit Dendrometer bestückten Bäumen zu messen wurden Hobos (Gerät zur Temperaturmessung) eingegraben und so eingestellt, dass alle 3 Stunden die Temperatur registriert wird.

Insgesamt wurden 1584 Bohrkerne geworben, die Früh- und Spätholzbreite gemessen, weiters die Gesamtjahrringbreiten daraus abgeleitet, die Serien datiert und mit den Standortsdaten verbunden.

Sowohl die Jahrring- als auch die Spätholzbreitendaten wurden - um baumaltersbedingte Effekte zu eliminieren - mittels einer regionalen Zuwachskurve, erstellt aus den erarbeiteten Serien, unter Berücksichtigung des Kambialalters der Werte standardisiert. Die so gewonnen trendbereinigten Serien wurden anschließend bezüglich ihrer Klimasensivität und anderer Effekte, z.B. des Einflusses der Wuchsstandorthöhe auf den Zuwachs, analysiert. Erstellt wurden auch Jahrringchronologien für die zwei Baumarten bzw. die Parameter Jahrring- und Spätholzbreite und diese mit regionalen Referenzchronologien verglichen. Die Vergleiche ergaben hohe Übereinstimmungen, speziell bemerkenswert waren die guten Ergebnisse des Vergleichs der Zillertaler Spätholzbreiten-Chronologien mit Jahrringdichtekurven aus dem Alpenraum.

Die Jahrring- und auch die Spätholzbreiten zeigen in der Regel eine kontinuierliche Abnahme mit der Seehöhe (Ausnahme: Zirbe unter ca. 1600 m ü.M.), wobei in manchen Jahren dieses Muster stärker ausgeprägt sein kann und in anderen Jahren kaum vorhanden ist. Im Mittel zeigt die Fichte sowohl für die Jahrring- als auch Spätholzbreite eine nahezu lineare Abnahme des Zuwachses um ca. 10-12% je 100 m Höhenzunahme des Wuchsstandortes. Dabei erbrachten die Daten sowohl bei der Fichte als auch bei der Zirbe keine wesentlichen Unterschiede im Wuchsniveau und Trend im Vergleich von Nord- und Süd-Exposition.

Die erarbeiteten RCS Jahrring- und Spätholzbreitenchronologien korrelieren deutlich positiv mit instrumentellen regionalen Temperaturzeitreihen. Die höchsten Werte – bis zu r= 0.74 – wurden mit den Spätholzbreitenserien und vor allem im Vergleich mit einem langen Sommermittel (Mai bis September) erreicht. Der beobachtete, deutliche Temperaturanstieg in den Jahrzehnten nach 1980 wird von den Jahrringchronologien deutlich nachgezeichnet. Eine Aufteilung der Fichten-Datensätze nach der Wuchsstandorthöhe – unter bzw. über 1580 m ü.M. – zeigte keine Unterschiede im Trendverhalten im Hinblick auf die letzten Jahrzehnte.

Anhand der Auswertung von den Hobos konnte einen Temperaturgradienten von 0.65°C pro 100 m Seehöhenunterschied nachgewiesen werden. Zudem konnten keine längeren Inversionslagen im Projektgebiet nachgewiesen werden. Eine zum Vergleich mit den instrumentell gemessenen Temperaturgradienten durchgeführte Konvertierung der gemittelten Zuwachswerte je Bohrprobe in Temperaturdaten zeigt für beide Baumarten am Beispiel der Spätholzbreiten einen übereinstimmenden Trend, d.h. Abnahme mit zunehmender Höhe. Während die Rate bei den Fichten-Spätholzbreiten mit ca. 0.54 °C/100 m knapp dem instrumentell bestimmten Wert entspricht fällt der Betrag für den gesamten Zirben-Spätholzbreiten-Datensatz deutlich geringer aus.

Aus den Dendrometerdaten wurde der Verlauf des Durchmesserzuwachses nach dem 1. April berechnet. An die Daten wurde ein logistisches Wachstumsmodell mit einer Asymptote, einem Wendepunkt und einem Skalenparameter angepasst. Im Projektgebiet lag die Asymptote zwischen 0.132 und 0.816, d.h. die Bäume leisteten einen Durchmesserzuwachs von 0.132 bis 0.816 cm. Der Wendepunkt variierte zwischen 48 und 141, er lag jedoch oft zwischen 70 und 90 Tagen. Das bedeutet dass 70 bis 90 Tage nach dem 1. April bereits die Hälfte des Zuwachses geleistet wurde. Der Skalenparameter, der angibt wie viele Tage es dauert um von 50 % auf 73 % des gesamten Zuwachses zu kommen, lag zwischen 12 und 47 Tagen.

2 Executive Summary

The last decades were characterized by rising mean temperatures and changing precipitation patterns. Climate change is of high relevance for mountain forest ecosystems. Reactions of tree growth may however be highly variable between species and other variables related to tree growth e.g. tree age, site (elevation, soil type…), competition between trees, or species mixture can alter reaction patterns. Reactions of tree growth to climate can be studied by analysing increment cores which allow to retrospectively analysing tree growth over many years and large geographic areas because they can be easily sampled. A more detailed analysis of within year climate-growth relationships can be obtained from dendrometers which hourly record changes in tree circumference Dendrometers however do not allow a retrospective analyse of tree growth, they have to read out each year and the possible sample size is therefore smaller.

For Austria two different climatic datasets are available: HISTALP (Historical instrumental climatological surface time series of the greater alpine Region) and INCA (Integrated Nowcasting through Comprehensive Analysis). The HISTALP dataset consists of monthly homogenized climate records and dates back to 1760, with a spatial resolution of 5' x 5' (~7 km x 10 km) (www.zamg.ac.at/histalp/). INCA is a tool that provides temporally and spatially high resolution weather analysis. The INCA dataset has a high spatial (1 km x 1 km) and temporal resolution (hourly) but offers data only since 2003 (Haiden et al., 2011).

In this study we used both sets of climate data and tried to combine the strength of both approaches to study tree growth by systematically sampling over 1000 increment cores in Gerlos and Zilltertal, along 24 altitudinal gradients ranging from 1300 m to the timberline and by installing 58 dendrometers in the project area.

The aim of the project was to study patterns of tree growth and to evaluate climate interpolation models. In mountainous regions already small differences in altitude, aspect and surface topography may have an effect on climate that might not be captured by climate interpolation models.

The analysis of increment cores with a response function analysis indicated that tree growth in the study area is mainly influenced by temperatures in May to September. June, July August temperatures show a strong correlation with tree-ring width, as they are the key months of the growing season. Particularly July temperature correlates significantly (r=0.55) with tree-ring width of Swiss pine and precipitation in August correlates significantly with tree-ring width of both tree species (r=0.34 for spruce, r=0.24 for pine). However, highest correlations between tree-ring variables and temperature are available for RCS-standardized latewood width data, e.g. 0.7 for Swiss pine as well as Norway spruce and the May to September temperature.

To the year ring data also a liner mixed basal area increment model and latewood width model was fit. For Norway spruce basal area increment depended on diameter at given year, cambial age, crown ratio, tree class, elevation and year. Swiss pine is similar to spruce except for tree class, which doesn´t play a significant role for pine in the explanation of BAI. LWP of Norway spruce was rather driven by age as size. As random effects, which improved significantly the models, were retained: tree ID, transect, site and calendar year. The random effects part, showed almost always the highest standard deviations for tree ID and calendar in every model. The grouping variables tree ID and year explained therefore the highest share of variability in the random effect part. Site and transect grouping showed a lower variability, indicating that between the site and even more for transects there was no major differences.

In the analysis of dendrometer data we fit a non-linear 3-parameter logistic growth model to each of the 272 growth patterns and estimated the cumulative diameter increment from the first of April dependent on the number of days since the first of April. Estimates for the asymptote parameter in Tirol were between 0.132 to 0.816, indicating that overall diameter increment between year and site in the study area was 0.132 to 0.816 cm. The point of inflection varied between 48 and 141. In the majority of cases it was however between 70 and 90 days. This means that between 70 and 90 days after the first of April half of the asymptotic growth was obtained. The scale parameter, which indicates the time required from 50 % to 73 % of the asymptotic growth, was between 12 and 47 days. Finally, we fit a mixed non-linear hierarchical growth model to the data and tested numerous different covariates for site tree and year.

3 Background and Aims

(max. 2 Seiten) Beschreibung von Ausgangslage, Aufgabenstellung und Zielsetzung.

Background

Models for prediction and scenario analysis play an important role in the current debate about climate change and its possible impacts. Against this background numerous impact studies applied on different ecosystems emerged. The fact that different types of models with different underlying assumptions can be used for the same purpose makes it increasingly difficult for policymakers to evaluate these studies (Medlyn et al. 2011). In this regard, comparative validation studies would help to expose a model specific strengths and weaknesses (e.g. Neumann 2010).

Impact studies usually use modelled data from climate models as their key driver for simulating climate change impact predictions. However, the modelled climate data can be a source of error and therefore increase the degree of uncertainty in the predictions of the climate change impact. As consequence, the validation of climate models is an important task to be fulfilled before climate data is used in predictions models as input variables for scenario analysis. Especially in policy-relevant impact studies a scrupulous validation of the climate model is of high importance (Knutti et al. 2010).

Regional climate models use the output of global climate models (spatial resolution 100 – 200 km) and downscaling methods to obtain climate data at a spatial resolution up to around 25 km (Rummukainen 2010). However, to investigate the impact of climate change at regional scale, e.g. studies that use regional forest inventory data to simulate the impact of climate change on the development of forest ecosystems, need climate data at a higher spatial resolution (e.g. Battles et al. 2009, Seidl et al. 2009). In this case data can be derived from spatial climate interpolation models (CIMs). This model type has been developed to interpolate meteorological observations between regional weather stations and at the same time to account for local site characteristics. Climate interpolation models are usually validated by cross-validation, i.e. by comparison of predicted and observed values from weather stations that have not been included in the data set used for interpolation (e.g., Chiu et al. 2009, Newlands et al. 2010, Petritsch and Hasenauer 2011). One central disadvantage of this validation method is that no error statistics can be given for locations without weather stations (Daly 2006). Particularly for mountainous regions, where the interaction between topography and climate has an important effect, knowledge about the quality and the accuracy of a climate interpolation model's output is essential.

For validation studies climatic data with high spatial resolution over many years is necessary. However in order to sample climate data, it requires complicated and expensive instrumentation prone to inaccuracy and biases (Daly 2006). In our case, tree ring data, a well-accepted climate proxy (e.g. Büntgen et al. 2005), could serve as a possible alternative to instrumental climate data to validate a climate interpolation model.

Aims

The aim of this study is to use data from increment cores and dendrometer measurements sampled along altitudinal gradients and at sites with different aspect as proxy data to validate a climate interpolation model (CIM) in terms of its predictions of temperature, precipitation and solar radiation. The sampled tree species were Norway spruce and Swiss pine at 4 high altitude regions near alpine barrier lakes in Tyrol, Austria.

Secondary objectives are derived from the main objective.

1) As CIMs haven´t been validated at such high spatial scale using proxy data the project intends to add methodological knowledge in this respect.
2) Dendrometer measurements allow observations of intra-annual stem diameter variations. Therefore it was intended to validate the CIM also in terms of its temporal resolution in order to make predictions of climate variables for hourly, daily, monthly or annual time steps.
3) Detect the strengths and weaknesses of the CIM performance regarding the climatic effect of elevation and aspect. This could help to improve the accuracy of future regional climate impact studies.
4) Enhance the scientific knowledge about growth trends in high elevation ecosystems by investigating growth variations at inter-annual, intra-annual and hourly resolution.

4 Content and results of the project

The project was split into 9 workpackages.

WP1 – Increment coring and dendrometer installation

Increment cores

The coring and dendrometer installation of the sample trees was realized in the first project year (April. 2012 – June. 2012). In total, 438 Norway spruce and 252 Swiss pines were cored. The proportion of sample size between Spruce and Pine as stated in the project application (50% Spruce, 50% Pine) could not be reached due to the fact that the number of Swiss pine was not as frequent as assumed (76% Spruce, 24% Pine). Increment cores were taken from plots in approximately 34m ± 17m altitudinal steps by extracting 2 cores from opposite sides of the stem from 3-4 trees (one tree with mean basal area and 2-3 trees with dominant height) per sample plot at breast height (1.3 m above ground slope upwards) using a standard increment borer. For this study only dominant trees with healthy crowns (→ maximization of the climate signal, reduction of noise caused by disturbances) were cored and sampling extended over 24 transects with 9-12 sample points (angle count sampling) in each transect. Transects were distributed over 4 regions with 6 transects in every region.

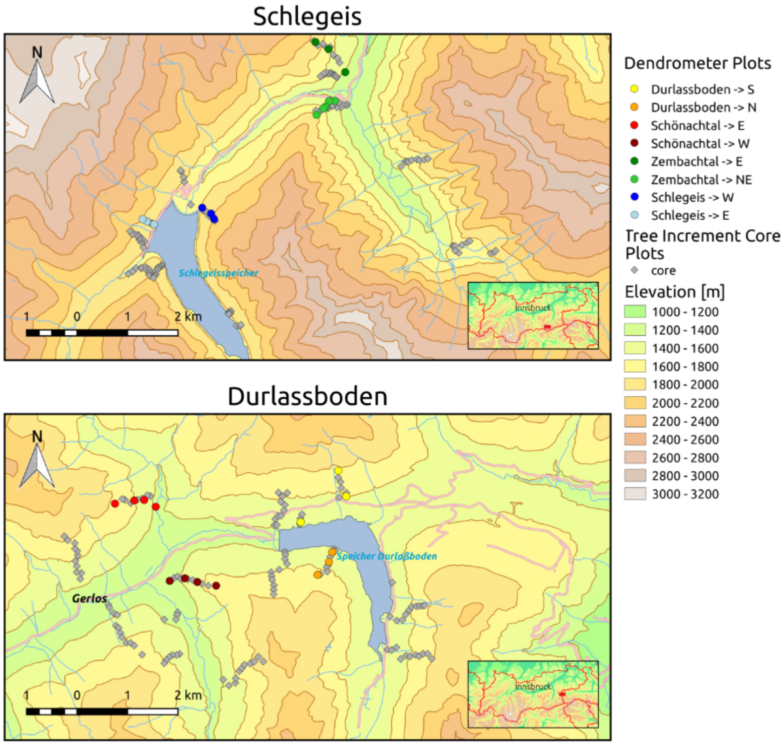


Fig 1. Locations of the transsects, sampling points, and dendrometers and their main exposition for Schlegeis (above) and Durlassboden (below).

Two regions were around the barrier lakes named Durlassboden (47°14’03’’N, 12°06’24’’E, 1400m - 1800m a.s.l.) and Schlegeisspeicher (47°01’30’’N, 11°42’34’’E, 1680 m - 2070 m a.s.l.) and the other regions were in two neighbouring valleys in about 4 km airline distance from the barrier lakes, namely Zemmbachtal (47°03’25’’N, 11°45’03’’E, 1300 m – 1950 m a.s.l.) and Schönachtal (47°13’39’’N, 12°03’16’’ E, 1300 m – 1960 m a.s.l.). The mean elevation difference from the lowest to the highest point in each transect was 331 m ± 113m.

At each sampling point, elevation, aspect, slope, geographic coordinates (latitude, longitude), micro relief, soil properties (water content, depth, group, humus, etc.), vegetation type and basal area was measured respectively assessed. Overall 261 plots were sampled for this study. The maps in **Fehler! Verweisquelle konnte nicht gefunden werden.** show the location of the transsects, sampling points, and dendrometer locations.

To determine cambial age at breast height, the trees were cored in pith direction i.e. tree centre, carefully avoiding branches and reaction wood. After extracting the increment cores from the sample trees they were properly packed in straws, labelled and brought to the BOKU, Forest Growth for further measuring.

Dendrometers

Additionally, 56 from the cored sample trees were equipped with band dendrometers with built in data logger (DRL 26, EMS Brno, CZ) measuring intra-annual growth variations (measurement of diameter variations at a resolution of 1 µm) and ambient air temperature (accuracy ±2°C). The dendrometers were fixed with a dendrometer increment band on the tree and the logger register changes in diameter development. In all, 36 Norway spruces and 20 Swiss pines were equipped with dendrometers.

The dendrometers were installed on 2 trees at 3-5 points (lowest, middle and highest altitude) of 8 transects (2 transects with different aspect at each of the 4 study sites). The mean altitudinal difference between the points was 131 ± 62m. The data loggers were set up to save diameter measurements and temperature hourly.

Fig. 2. Dendrometer DRL 26 (left) and HOBO Pendant data logger (right).

Hobos

The installation of Hobo data loggers (HOBO Pendant data logger, Onset, USA) was not mentioned in the original project application. They were installed by BOKU, Meteorology in close distance (~0.3-2 m) to the trees equipped with dendrometers in the same number and were set up to measure top soil temperature in 10 cm depth every 3 hours for the duration of the project. To ensure continuous measurement intervals, the batteries were replaced annually.

WP2 – Tree ring measurement

Tree-ring measurement was carried out at BOKU, Forest Growth. In all, 872 tree-ring series from 438 Norway spruce trees and 497 tree-ring series from 252 Swiss pines were prepared (surface sanded) for measurement. Tree ring measurement (early-and latewood width) was carried out to the nearest 0.01 mm with standard measuring tables (LINTAB table and Johann´s Digitalpositiometer) and using TSAP-Win software (Rinntech) by two students.

The raw data was checked for false or missing rings, synchronized, dated and standardized using the RCS-method (regional curve standardization; e.g., Briffa and Melvin, 2011) by Thomas Pichler under the supervision of project partner Kurt Nicolussi at the University of Innsbruck, Institute of Geography.

Finally, the processed measurements were saved species-wise in separate files with raw ring width, latewood widths and RCS-detrended measurements and made available for all partners on an FTP-server.

WP3 – Inspection of the installed dendrometers and reading data

Inspection and the readout of the dendrometers was realized twice a year, one time at the beginning of the vegetation period in spring (May) and the second time at the end of the vegetation period in autumn (September, October). The dendrometers were tested in terms of their operability and condition (battery charge, fixation on the tree). The data was read out using a field laptop with infrared connection and checked for plausibility on site. The dendrometers measured ambient temperature and changes in stem diameter with a temporal resolution of one measurement per hour. In all, the dendrometers were little prone to dysfunctions and generated reliable data for later analysis. At the end of the project duration 53 from the initially 56 dendrometers were working properly. 2 dendrometers were lost due to wind throw events and one dendrometer stopped logging in May 2014 due to malfunction. Despite of this loss, 56 time series are available for the analysis with the small disadvantage that 3 series are shorter.

In the same time, while inspecting the dendrometers, the Hobos were read out and data checked for plausibility. The batteries were also changed in order to avoid data loss. After battery change and data read out, the devices were re-buried on the same place. Similar to the dendrometers, only 2 from the 56 installed Hobos were lost due to wind throw events and remained untraceable. One Hobo needed to be relocated due to the construction of a mountain bike trail. The advantage of having 2 units of each device (Dendrometer and Hobo) per sample point is that in case of a loss a reserve exists and every measurement has a control value.

WP4 – Data management and control

The aim of this work package was to generate a clean database for further statistical analysis. After tree-ring measurement and standardization the tree-ring series, the dendrometer and Hobo data were checked for plausibility and the data was structured for further analysis. Cambial age was determined by counting the annual rings from the outermost ring to the pith. Preconditions are that bark and pith must be present. If the pith is not present, pith offset (segment between the innermost tree-ring of the core and pith) must be estimated in years and in distance depending of the growth rate of the individual tree-ring series. For this purpose, the tree-ring series are covered with transparent masks with drawn circular tree-rings and the missing rings are estimated. Implausible or obviously erroneous data was removed from the dataset or corrected. Data management and control was mainly done using Microsoft Excel and R.

<u>Tree-ring measurements:</u>
After measurement of early- and late wood width the tree-rings series were dated. Values which were obviously erroneous were removed. The tree-ring series cover the period from 1726 to 2011 for Norway

spruce (872 tree-ring series) and from 1678 to 2011 for Swiss pine (497 tree-ring series), whereby the period from 1850 to 2011 is covered by mostly all the trees. The altitudinal distribution of the series varies between 1323 m to 1951 m for Norway spruce and 1582 m to 2069 m for Swiss pine. Average ring width of Norway spruce was 1.51 mm and for Swiss pine 1.42 mm. For both species, ring width decreased with elevation. A preliminary age related growth trend was removed by standardizing the tree-ring series using the RCS-method. By aligning all individual tree-ring series by cambial age one and calculating the yearly mean values, a regional growth curve (RC) was computed for both tree species and for the total tree-ring width as well as for the latewood width data. A regional curve describes the age-related, biological growth trend, typical for a given species, site and region. For further analysis, the series were merged with individual tree specific data (e.g. crown ratio, height-diameter-ratio…) and site information (e.g. soil properties, stand density…) using R.

Dendrometer measurements

Dendrometer data management was in constant progress. After the logger readout the recorded diameter variations and temperature measurements were added to the previous measurements. The time series were compiled into one dataset, increment band offsets from the installation were deducted and data was imported into R and checked for plausibility.

WP5 – Validating the climate interpolation model, part 1 – using tree ring data

Main focus of this work package was (1) to identify the key climate variables that correlate with tree growth, (2) to implement climate interpolation models for the study region and (3) to evaluate the performance of the CIMs by bringing together the data.

1. The major strengths of tree-rings as climate change indicators are the capability to perform annually resolved dating, the existence of large geographic-scale patterns of synchronic interannual variability, the increasing availability of extensive networks of tree-ring chronologies covering large parts of the terrestrial globe and the possibility of using simple models of climate-growth relationships that can be easily verified and calibrated (Hughes 2002). On the other hand, tree rings have the disadvantage that they only record certain wavelengths of climate variability and that the climate signal in tree-ring data reflects complex biological responses to climate forcing. In the first step we therefore tried to identify which wavelengths of climate variability were contained in tree-ring data and to analyse the biological responses to climate forcing.
   At high alpine sites, temperature is usually reported to be a limiting factor for tree growth (e.g. Oberhuber & Kofler 2003, Carrer & Urbinati 2004, Büntgen et al. 2004, Leal et al. 2007). Similar to previous studies, we related temperature and precipitation variables over the time period of instrumental record to annual tree-ring growth using response function analysis (Biondi and Waikul 2004). Particularly temperatures in June, July and August show a strong correlation with tree-ring width, as they are the key months of the growing season. In the study area, precipitation in August correlates significantly with tree-ring width of both tree species (r=0.34 for spruce, r=0.24 for pine), however, correlations with temperature data are significantly higher, e.g. 0.71 (August) for the

Swiss pine LW data. Correlation results of the RCS-detrended LW data of both species are usually higher than the results achieved for RW data. Significant correlation results of about 0.7 can also be shown for the combination of RW and LW data and a long summer (May to September) season (Fig. 3). Highest correlations are recorded for the combined PCAB/PICE LW chronology (period 1855-2011: single year: r=0.75, 30 year smoothed series: r=0.94). Figure 4 shows these series after scaling of the PCAB/PICE LW chronology against the instrumental temperature series (May to September average).

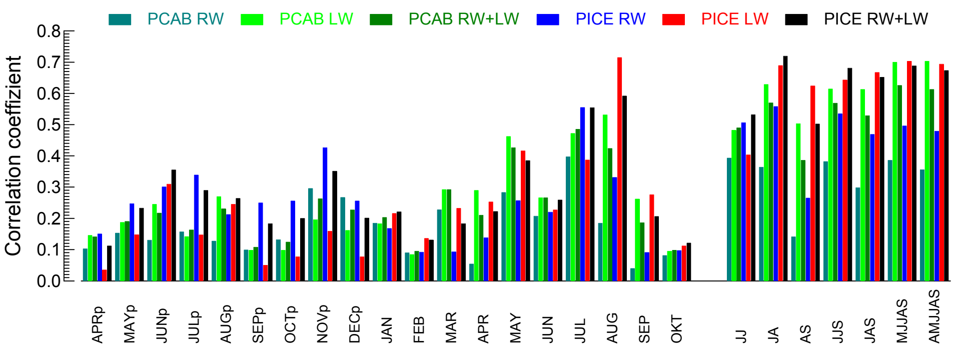


Fig. 3. Response function analysis results of the Norway spruce (PCAB) and Swiss pine (PICE) ring width (RW), latewood (LW) and averaged RW/LW chronologies established with RCS-detrended single series and instrumental temperature data (period 1855-2011).

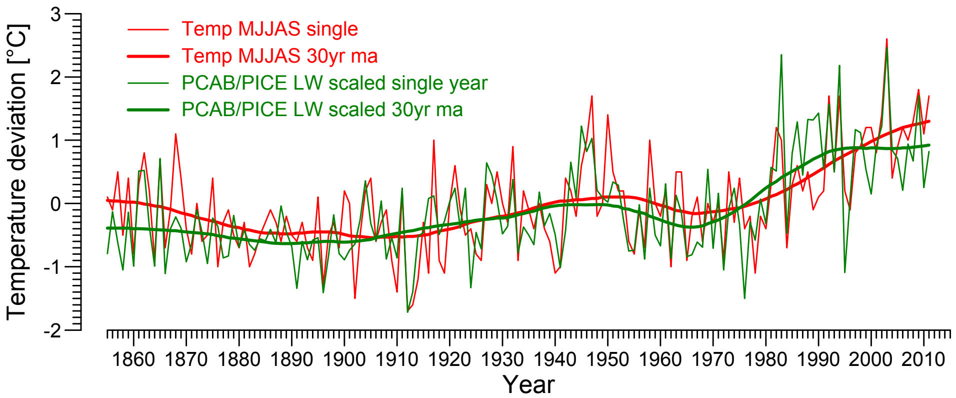


Fig. 4. Comparison of the instrumental temperature series (May to September average) and the Norway spruce / Swiss pine (PCAB/PICE) latewood (LW) RCS average chronology after scaling of the tree-ring data against the temperature record.

The correlation results prove that tree-ring data of our sampling sites record a temperature signal. Moreover, the results for the latewood chronologies are exceptionally high and also outstanding regarding the seasonal coverage (May to September).

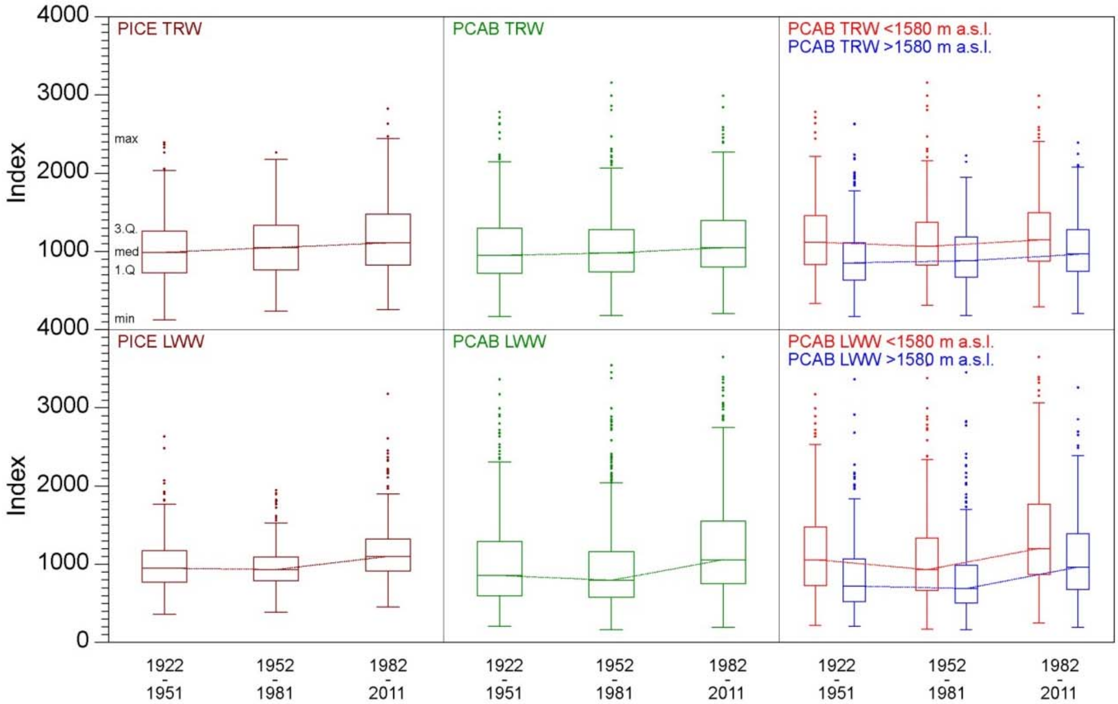


Fig. 5. Analysis of growth rates in different time periods (1922-1951, 1952-1981, 1982-2011). Tree-ring (TRW) and latewood (LWW) values are highest during the last period indicating a positive reaction of tree growth of Swiss pine (PICE) as well as Norway spruce (PCAB) on recent climate change. A splitting of the PCAB data indicates elevation-related different growth levels (see also WP 6) but similar reactions on recent climate development.

We also analysed if and how similar the growth trends found for the whole species data sets in the 20th and early 21st century (e.g., Fig. 4) are in different elevation-related sub-groups. We investigated the last 90 calendar years of our data sets by splitting this time period into three sections (1922-1951, 1952-1981, 1982-2011). The analysis of total tree-ring width (TRW) as well as the latewood width (LWW) data of the three time periods based on sRCS standardized data shows that TRW but especially LWW values are highest during the relatively warm last three decades (Fig. 5). Even the spruce trees at lower elevated sites (ca. 1300 to 1580 m a.s.l.) do not show clear proves for suffering in relation to recent warming.

For the identification of regional-climatic events and influential climate factors on tree growth, pointer years were calculated for the two tree species. Pointer years, also known as Weiserjahre, were defined as years in which at least 70 % of the tree-ring series showed a growth decrease/increase of more than 10 % compared with the previous and following year. Positive pointer years for Norway spruce were 2001, 1982, 1921, 1904, 1822; negative pointer years were 1995, 1984, 1954, 1948, 1918, 1913 and 1843; For Swiss pine positive pointer years were 1994, 1982, 1976, 1958, 1935, 1927, 1921, 1914 and 1869. Negative pointer years were 1996, 1948, 1920, 1917, 1913, 1851 and 1843. The results showed that spruce and pine reacted differently on climatic influence and that they have very few common pointer years (e.g. positive 1982, 1921, negative 1948, 1913 and 1843). In pointer years tree growth doesn´t forcibly follow the elevation trend (decreasing tree ring width with altitude). Some years show same increment regardless of altitude.

The dendrometer and hobo measurement revealed a general temperature gradient of -0.65 °C/100m with increasing altitude in the study area. Also, it doesn´t seem that the project area is influenced by long lasting atmospheric inversion situations.

For the analysis of site-growth relationships a site index for each of the sample plots was calculated. Site index is defined as the dominant stand height at age 100. It is an indirect and easy way to determine site productivity. In all of the 4 study areas site index decreased with elevation, but there was no significant difference of site index with aspect. As would be expected, tree ring width decreased with site index.

2. For the validation of the climate interpolation model the HISTALP (Historical instrumental climatological surface time series of the greater alpine Region) and INCA (Integrated Nowcasting through Comprehensive Analysis) dataset were used. These datasets consists of two long-term meteorological time series. The HISTALP dataset consists of monthly homogenized temperature, pressure, precipitation, sunshine and cloudiness records. The longest temperature and air pressure series extend back to 1760, precipitation to 1800, cloudiness to the 1840s and sunshine to the 1880s with a spatial resolution of 5’ x 5’ (~7 km x 10 km) (www.zamg.ac.at/histalp/). Originally INCA is a tool that provides temporally and spatially high resolution weather analysis and weather forecast with special consideration of regional and small-scale geographical effects (Haiden et al. 2011). In INCA all available weather information are incorporated as data from weather stations, radar and satellite, as well as detailed information on natural features.The INCA dataset has a high spatial (1 km x 1 km) and temporal resolution (hourly for temperature, radiation and relative humidity; precipitation every quarter of an hour) but offers only data since 2003. Merging the two datasets offered the possibility to have meteorological data dating back to the mid-18th with the high spatial resolution of the INCA dataset. This was done by superimposing local patterns of the INCA dataset on a monthly basis to the long-term time series of the HISTALP dataset (i.e. localization). Temperature was localized additive and precipitation multiplicative. The mean of both variables in the localized dataset in the area of the grid box equals the values of the HISTALP grid box. In addition to localization, potential evapotranspiration was computed on basis of the localized data using Thornthwaite method. The difference of accumulated precipitation and accumulated potential evapotranspiration is called climatic water balance and is an indicator for water available to the vegetation. Fig. 6 shows the mean climatic waterbalance for the region. This shows that water is in general not a limiting factor in the study region, since it is always positive.

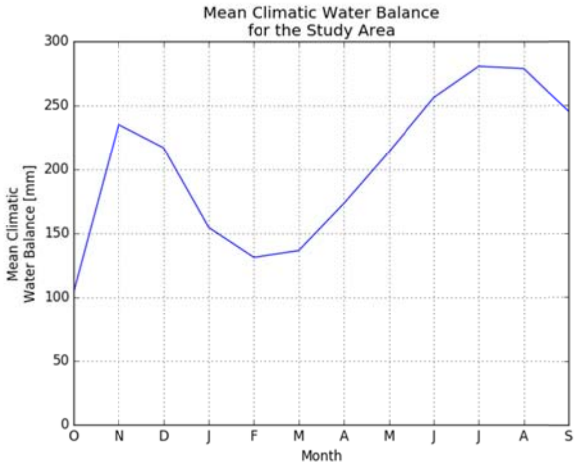


Fig. 6. Mean Climatic Water Balance for the region.

3. To analyse if the tree-ring data contain not only a temporal but also a regional signal we applied the scaling factors established for the transformation of the tree-ring series, i.e., the LW chronologies, into proxy-temperature records, i.e., May to September period (Fig. 4), on the mean values of the RCS-detrended (to avoid age-related bias) tree-ring series and plotted the results against the elevational position of the tree-ring data (Fig. 7). The results display a wide spread of the scaled single LW mean values but also an elevational decrease of the expected temperatures. However, the results found diverge between the two species: Swiss pine LW just display a gradient of ca. 0.15°C/100 m whereas Norway spruce LW indicate a much stronger gradient: ca. 0.54°C/100 m. The latter one is nearly in the same range as it is known from comparisons of temperature station data (ca. 0.6/100 m for the period May to September) or from our hobo measurements (0.65 °C/100, see WP 5, 1.).

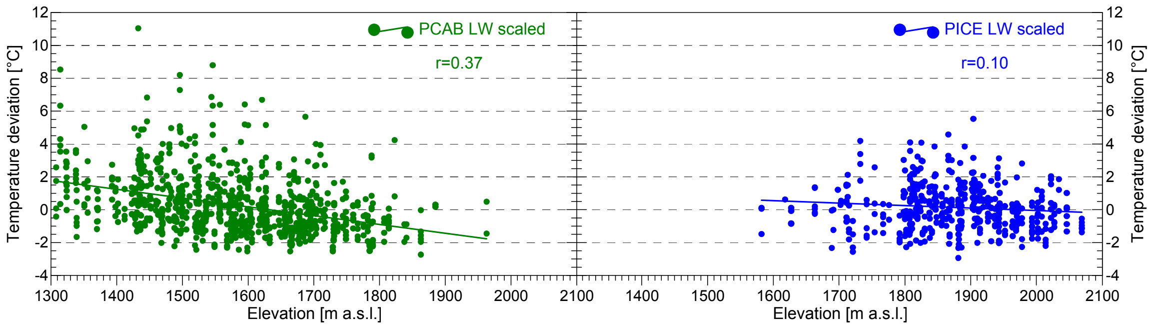


Fig. 7. Elevational temperature trends for Norway spruce (PCAB) and Swiss pine (PICE) latewood (LW) after transformation of mean values of RCS-detrended series into temperature values by applying scaling factors.

WP6 – Growth trends in high elevation ecosystems of Norway spruce and Swiss pine

This work package addresses the investigation of growth trends in high elevation ecosystems of Norway spruce and Swiss pine. Additionally to the tree-ring series measurements obtained from the increment cores (tree ring width and latewood width), tree related measurements (DBH, cambial age, crown ratio...) and site factors (e.g., aspect, slope, water balance, competition...) were included in the analysis.

To achieve this goal, two approaches were selected. One method is a dendrochronological approach using tree-ring widths and the single regional growth curve standardization method (sRCS) and the other is a statistical modelling approach by analysing growth rates over time in dependency of tree related measures and site characteristics.

Dendrochronological approach

The tree-ring width chronologies display high similarities with other Alpine chronologies of the same species. On the other side the Norway spruce and Swiss pine late wood chronologies showed high correlations with alpine maximum density chronologies (Fig. 8).

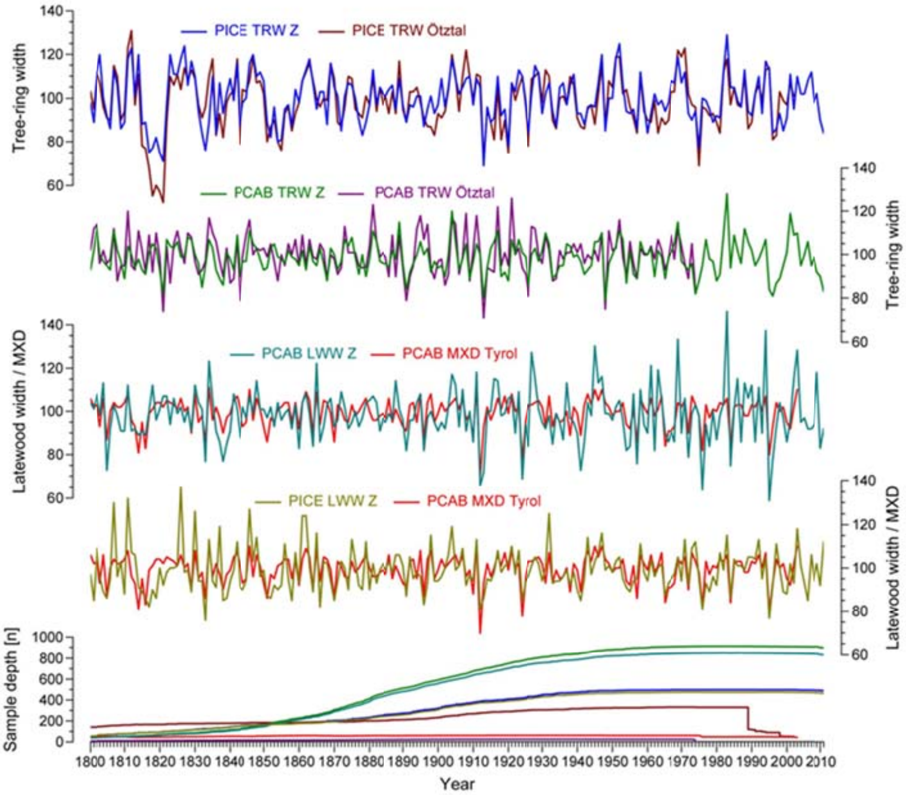


Fig. 8. Comparison of the Norway spruce (PCAB) and Swiss pine (PICE) tree-ring and latewood width chronologies from the Zillertal (TRW/LWW Z) with other regional tree-ring records (all chronologies high-pass filtered). PICE TRW Ötztal: Nicolussi et al. 1995, Nicolussi/Thurner 2012; PCAB TRW Ötztal: Siebenlist-Kerner 1984; PCAB MXD Tyrol: Esper et al. 2007.

Altitudinal and aspect related effects on growth were investigated by applying single regional growth curve (RCS) standardization methods (to avoid tree-age related bias) on the tree-ring measurements from the dataset. The RCS method supposes to remove the long-term biological age effect from the tree-ring series and to keep climatic related, mid- and high frequent growth signals (decadal to annual signals in tree-rings).

For Norway spruce the results indicate an almost linear decline of the total tree-ring width and the late wood width with elevation (10-12% per 100 m). Swiss pine, however shows maximum mean growth around 1800 m a.s.l. for tree-ring width as well as for late wood width and lower values at lower and higher elevations. Moreover, the data sets suggests no significant aspect-related effects on tree growth after splitting the data in north and south faced data sets (Fig. 9). However, a further aspect-related differentiation of the data sets in several sub-groups (results not shown) leads to a more complex picture. This could partly be caused by the smaller datasets that are potentially influenced by individual trees growing under very local conditions

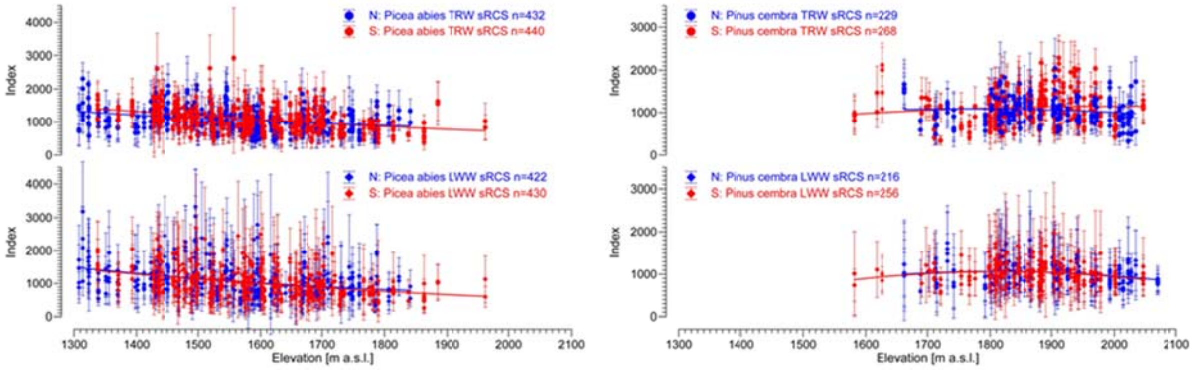


Fig. 9. Single-RCS standardised tree-ring (TRW) and latewood width (LWW) data (average and standard deviation, based on core series) of Norway spruce (*Picea abies*, left panel) show clearly elevation-related growth trends but no distinct differences between data from north or south-facing sites. The results for Swiss pine (*Pinus cembra*, right panel) are similar, however, they indicate highest growth rates for this tree species around 1800 m a.s.l.

Growth model

Basal area increment is a widely used response in growth models, as it is a direct indication of the wood production of the tree in that year, assuming the wood production at breast is characteristic for the wood production along the entire stem (Visser, 1995). Basal area increment is largely influenced by early wood development and spring temperatures whereas latewood development in mountainous starts in early summer till midsummer and ends in early autumn. Both tree growth and late wood growth depend on tree species, age competition and site (including climate). Basal area increment models are usually the core models for individual tree growth models. Individual tree growth models are a modelling framework that combine models for basal area increment, height increment, mortality and regeneration and allow the prediction of stand growth for different management scenarios (e.g. Vospernik and Reimoser 2008).

The aim of this approach was to fit a basal area increment model to the tree ring data and draw conclusions on past climate impact on tree growth rates by comparing the elevation effect on tree growth between different periods. In forest growth modelling tree basal area increment (BAI) is typically modelled as a function of tree size, competition and site variables (Wykoff, 1990) (Monserud & Sterba, 1996).

$$BAI = Size + Competition + Site$$

In BAI models, especially in uneven aged stands, BAI is rather driven by tree size (in our case the current diameter at a given year) than by cambial age (Mencuccini, et al., 2005). The model assumes a quadratic relation between BAI and DBH as a proxy for development time (Wykoff, 1990). Competition is represented by crown ratio and social class. Site variables are aspect, vegetation and soil properties. The aim of the base model is to detrend the individual tree ring series from their age/size, competition and site effect.

In order to incorporate the maximum number of trees and to have a nearly balanced number of measurements per year, the time span is limited to the period from 1960 to 2009 (50 years). To avoid irregular juvenile growth due to suppression, measurements below a cambial age of 30 and increments below a DBH from 8 cm were excluded from the analysis. After filtering trees with less than 30 measurements were also removed. After filtering, 402 trees and 19975 observations for Norway spruce and 237 trees and 11815 observations for Swiss pine were available for further analysis. As generally two increment cores were taken per tree, the mean annual growth rates were calculated by averaging measurements of both increments cores. The calculation of BAI was performed using the bai.in-function from dplR-package in R (Bunn, 2008), (R Core Team, 2015).

In all, 4 different models were calculated. For each tree species a BAI-model and a LWP-model was developed. For the models a linear mixed model approach was chosen. A mixed model considers two parts, (i) a fixed effect part including the parameters about which conclusions are to be drawn and (ii) a random effect part in which the samples are combined to groups derived from a larger population with an estimated variance for each group. The linear mixed model also controls for non-independence of the repeated measurements among the individuals (in our case multiple tree ring measurements per tree) by considering a random slope for each tree. This controls the effect that some trees grow faster or slower as others. The sample design of this study considers as a 3-level hierarchical structure. Tree ring measurements are nested within trees (level 1), those are nested within sites (level 2), which are again nested within transects (level 3). The random effect part of the models reflects this structure and accounts for the variability of trees, sites and transects. Because of the heavily skewed distribution the dependant variables were log-transformed before fitting the models. The model is fitted by progressively adding the variables in the model and analysed for their significance. In the case of non-significance they are removed from the model. Multicollinearity between independent variables was analysed using Variance Inflation Factor (VIF) and variables with a VIF<5 were removed from the model. Modelling and analyses were performed with R-statistics using the lme4-package (Bates, Maechler, Bolker, & Walker, 2015), (R Core Team, 2015).

To compare elevational growth trends over the last 5 decades (1960-69, 1970-79, 1980–89, 1990-99, 2000-09) an interaction term was added to the base model. The analysis of this term should provide information about decadal growth patterns and their effect on growth rates. To investigate these effects the decades are integrated as categorical variables with 5 levels and elevation as continuous variable in the analysis.

Tab. 1. Fixed and random parameters and their corresponding standard error and standard deviation

		Norway spruce				Swiss pine			
		BAI		LWP		BAI		LWP	
		Estimate	Std. Error	Estimate	Std. Error	Estimate	Std. Error	Estimate	Std. Error
Fixed Effects	Intercept	2,210871***	0,325281	-4,607699***	0,207324	4,741281***	0,284441	-7,700173***	0,322491
	log(DBH)	1,667572***	0,03049			0,689399***	0,027877	0,238673***	0,046382
	DBH^2	-0,016173***	0,001193						
	log(Age)			0,355637***	0,044465			0,67757***	0,065228
	log(Cambial Age)	-0,991912***	0,063816			-0,893989***	0,056789		
	Social rank	-0,115592***	0,023993						
	log(Crown ratio)	0,410105***	0,063386			0,299114***	0,056534		
	Elevation/100	-0,05075***	0,014176	-0,092818***	0,018967	0,030106	0,019947	-0,079092**	0,023979
	70-79	-0,097643*	0,037887	-0,078149	0,069299	-0,069509 .	0,040395	0,091095	0,05524
	80-89	0,033132	0,038107	0,032077	0,069752	0,048589	0,040576	0,094116 .	0,05561
	90-99	-0,127729**	0,038477	0,090416	0,070397	-0,02531	0,040843	0,176435**	0,056152
	00-09	-0,110978**	0,038951	0,0922	0,071175	0,003825	0,041145	0,124922*	0,056762
	Elev:70-79	0,011734***	0,003521	-0,025315***	0,006286	-0,01853**	0,00588	0,006883	0,010775
	Elev:80-89	0,030502***	0,003537	-0,011908 .	0,006353	-0,079176***	0,00588	0,076463***	0,010774
	Elev:90-99	0,012722***	0,003578	-0,015578*	0,006453	-0,037367***	0,00588	0,062944***	0,010774
	Elev:00-09	0,03276***	0,003623	-0,027264***	0,006545	-0,025504***	0,005887	0,052288***	0,010786
Random Effects			Std. Dev.		Std. Dev.		Std. Dev.		Std. Dev.
	tree		0,21		0,2811		0,2781		0,277
	Transect		0,06767						
	Site		0,12908		0,2283				0,1135
	Year		0,08398		0,1536		0,08931		0,1211
	Residuals		0,19783		0,3523		0,18975		0,3487
AIC		-6054,5		16760,6		-4407,4		9808,9	

Growth model results

4 Models were fitted describing tree growth in terms of BAI and LWP. In our case, different site effects like soil quality, water content, soil depth, etc. played a minor part in explaining growth rates. For Norway spruce, diameter at given year, cambial age, crown ratio, tree class, elevation and year had a significant effect on annual BAI. Swiss pine is similar to spruce except for tree class, which doesn´t play a significant role for pine in the explanation of BAI. LWP of Norway spruce was rather driven by age as size.

As random effects, which improved significantly the models, were retained: tree ID, transect, site and calendar year. The random effects part, showed almost always the highest standard deviations for tree ID and calendar in every model. The grouping variables tree ID and year explained therefore the highest share of variability in the random effect part. Site and transect grouping showed a lower variability, indicating that between the site and even more for transects there was no major differences.

An overview of the parameters, coefficients and errors is given in Table 1. Model selection was based on Akaike information criterion (AIC). The fixed part of the fitted models used for the analyses were as following for Norway spruce:

BAI-base model

$$\ln(BAI+1) = b_0 + b_1 * \ln(DBH_t) + b_2 * DBH^2 + b_3 * \ln(Cambial\ Age) + b_4 * social\ ranking + \quad b_5 * \ln(Crown\ rati)o$$

LWP-base model

$$\ln(LWP) = b_0 + b_1 * \ln(Age_t)$$

For Swiss pine:

BAI-base

$$\ln(BAI+1) = b_0 + b_1 * \ln(DBH_t) + b_2 * ln(Cambial\ Age) + b_3 * \ln(Crown\ ratio)$$

LWP-base

$$\ln(LWP) = b_0 + b_1 * \ln(DBH_t) + b_2 * \ln(Cambial\ Age)$$

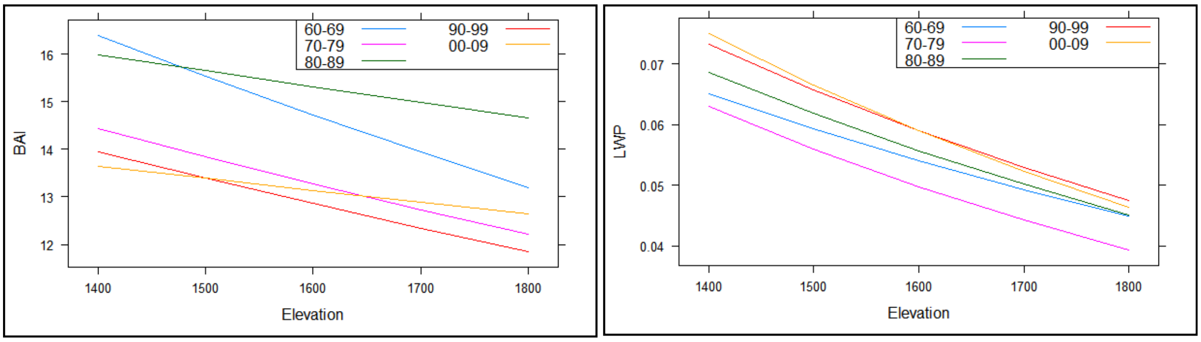


Fig. 10. Norway spruce: left panel: BAI; right panel: LWP.

Regarding the elevational effect on Norway spruce, a clear trend of decreasing growth rates with increasing elevation could be found. The interaction of decade and elevation showed significant differences between the decades, in which especially the 60s and 80s were periods with stronger growth compared to the 70s, 90s ,00s (Fig. 1010). Significantly different slopes against the reference period (60s) were detected. As the 60s were characterized with the strongest decrease of BAI in dependence of elevation, the following periods showed a lighter decline with elevation. Overall growth performance was highest in the 80s.

LWP shows a decreasing trend with altitudes in all of the 5 periods, in which the 90s and 00s decades show a significantly stronger effect of elevation on LWP (Fig. 10). Also the 90s and 00s have the highest LWP, especially in lower regions. The 70s were the period with the slightest LWP

Concerning BAI Swiss pine shows divergent trends in the analysed decades (

Fig. 11). In contrast to the 60s, with increasing growth rates over elevation, the 80s are characterized with decreasing growth rates. The last 2 decades (90s, 00s) show similar trends at a lower level. The 70s decade was the decade with lowest BAI in the analysed periods

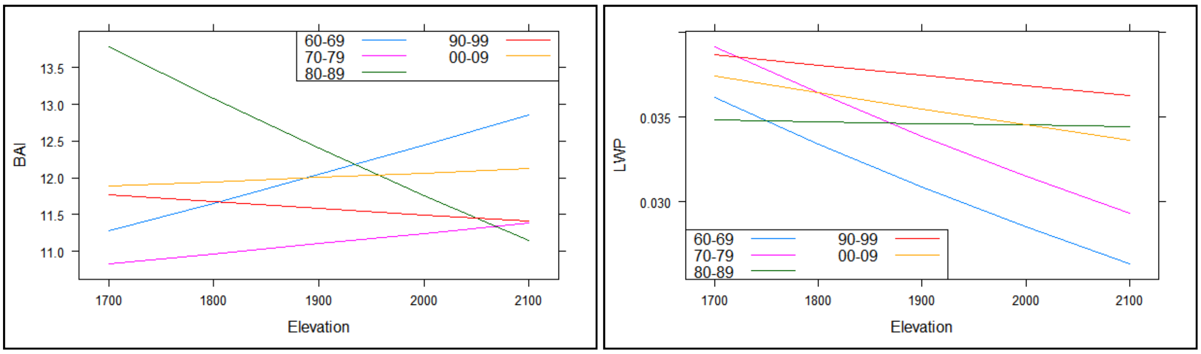


Fig. 11. Swiss pine: left panel: BAI, right panel: LWP

LWP of Swiss pine shows only small effects following the elevation gradient with weaker getting elevation effects on LWP (Fig. 11). The 80s even showed no effect of elevation on LWP. The last decade (00s) showed the LWP over the elevation gradient.

<u>Growth model interpretation</u>

In mountainous regions temperature is usually the limiting factor for tree growth. This effect is also reflected in the results in background of climate warming. The different slopes of the elevation-decade interaction can provide evidence for various weather conditions that prevailed during the periods. Shallower slopes could be an indicator for balanced temperature between lower and higher elevations. Steep slopes are an indicator for a strong climate contrast between lower and higher elevation, which finds it´s expression in a strong elevation effect within the growth models.

Norway spruce and Swiss pine show 2 different growth trends in dependence with increasing elevation. Whereas Norway spruce presents a clearly decrease of growth rates (BAI and LWP) with elevation, such a trend could not be detected for Swiss pine. Swiss pine shows divergent growth trends in the last 5 decades and a clear trend depending on elevation could not be found. Also, the magnitude in which elevation affects growth rates (BAI and LWP) from Swiss pine is lower compared to Norway spruce. This is partly due to the fact Swiss pine has its growth optimum at around 1850 m a.s.l. and lower increments around (see Dendrochronological approach). Elevation, as main effect, has no significant influence on BAI for Swiss pine.

The higher LWP in the 90s and 00s for both tree species may indicate the change to a longer growing season until later autumn compared to the past periods. However, that doesn´t imply that higher LWPs result in higher BAIs. It is rather the contrary; the last decades are characterized by decreasing growth rates.

Another uncertainty is the lack of information about possible disturbances in the stands. Temporarily decreases in growth rates can hardly be explained. Growth depressions can result from various reasons (e.g. insect outbreak, wind throw events, thinning measurements...). These effects could partly be intercepted through the use of sample plot (site) as random effect, because most disturbances were detectable in every tree within site and also during the same time.

Also information about tree shape and competition effects in the past is unknown and must be replaced by actual tree characteristics like crown ratio and social rank and assume the same values in the past.

WP7 – Hourly and intra-annual growth variation of Norway spruce and Swiss pine at high elevation sites

Continuous monitoring of stem radial variation throughout the year is crucial for understanding the tree's reaction to short-term changes in environmental conditions such as temperature, soil water content and rainfall. This monitoring can be straightforward using automatic dendrometers. These instruments measure stem radial variation composed of diurnal rhythms of water storage depletion and replenishment (Kozlowski and Winget, 1964) and seasonal growth (Dünisch and Bauch 1994). Because of reversible stem shrinking and swelling, dendrometers have been criticized when used to measure short-term growth rates (Mäkinen et al. 2003); because of their usefulness dendrometers have been used extensively to assess growth-climate relationships. One difficulty with dendrometers is to identify crucial phenological events such as cambial growth onset and ending. There are different approaches to extract growth signals. Two approaches commonly used are (i) daily approaches which consist of extracting one value per day from the time series and (ii) the stem cycle approach which is based on the patterns of shrinkage and swelling (Deslauriers et al. 2007). In the project proposal we suggested to follow the first approach, and to base our investigations on 48 dendrometers and 2 consecutive growth periods and analyse the effect of species, tree size and site variables.

For the final analysis in this work package we pooled the whole dendrometer data available at Boku, Forest Growth. The dataset include data from 108 dendrometers with 1-5 consecutive growth periods, resulting in 272 yearly growth patterns to analyse. From the raw data we calculated cumulative diameter increment and cumulative basal area increment since the 1st of January and 1st of April. From the temperature measurements we calculated the growing season by following a common definition of the growing season as (a) all days with a mean temperature > 5°C, and (b) by following the approach of v. Wilpert. He states that the growing season starts if the seven-day moving average daily temperature is greater than or equal to ten degrees centigrade; and growing season stops if either the seven-day moving average temperature is less than ten degrees centigrade on five consecutive days or if the limiting-daylight criteria is met which is set at 6th of October. Once the growing season has stopped it may continue again if the seven-day moving average daily temperature rises above ten degrees centigrade. In addition v. Wilpert also states that the growing season also stops if soil water tension is below -1100 Hektopascal on 5 consecutive days. However, we did not have the necessary data to include this criterion in the analysis. For all sites we calculate site index using the appropriate regional yield table.

Vegetation periods differed markedly between the two approaches and between years. In the project area the vegetation period according to v. Wilpert was 81 days in 2013, 67 days in 2014, and 93 days in 2015. The vegetation periods obtained following the first approach was considerably longer.

Because we analysed elevational gradients, the vegetation period also varied considerably differed between sites.

Previous approaches to analyse dendrometer data (Van der Maaten 2013, Wipfler et al. 2009), fit a 2-parameter cumulative Weibull distribution for each dendrometer and year. However, we did not find this approach flexible enough to describe growth patterns in our data set. We therefore fit a non-linear 3-parameter logistic growth model for each of the 272 growth patterns and estimated the cumulative diameter increment from the first of April dependent on the number of days since the first of April. Fig.12 shows that this approach fits different growth patterns well. Estimates for the asymptote parameter in Tirol were between 0.132 to 0.816, indicating that overall diameter increment between year and site in the study area was 0.132 to 0.816 cm. The point of inflection varied between 48 and 141. In the majority of cases it was however between 70 and 90 days. This means that between 70 and 90 days after the first of April half of the asymptotic growth was obtained. The scale parameter, which indicates the time required from 50 % to 73 % of the asymptotic growth, was between 12 and 47 days.

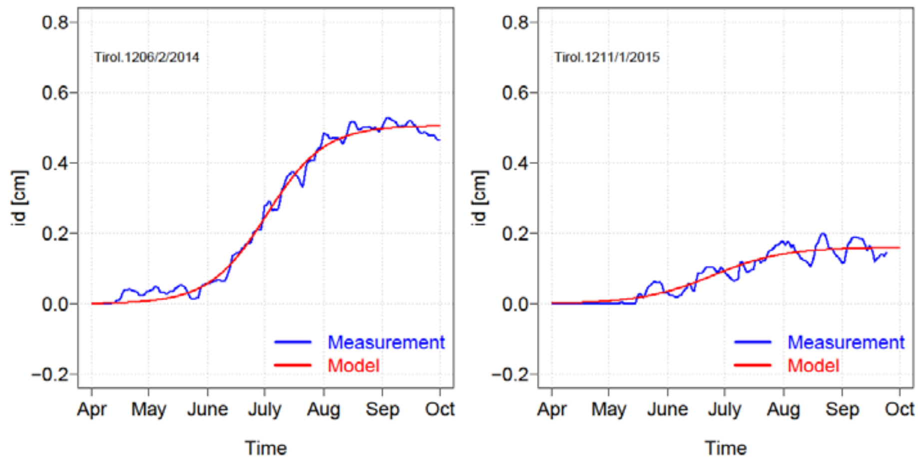


Fig. 12. Measured and modelled dendrometer data

Finally, an overall model for cumulative diameter increment was developed using a non-linear mixed hierarchical approach with random effects at the site, plot, tree and year level.
We tested numerous different covariates for the model: At the plot level we tested the effect of site, aspect, slope, elevation, site index, age, and basal area. At the tree level we tested the effect of tree species, dbh, tree height, height:diameter ratio and crown ratio. At the year level we tested for year, length of the vegetation period in the year and temperature sum during the vegetation period for both definitions of the vegetation period.

For the final publication it is planned to also include precipitation during the vegetation period and potential evapotranspiration in the model. This data will be obtained in the following two weeks for the additional dendrometer sites and then the model will be finalised and published.

In addition to the work planned for this project and as follow-up it is also planned to analyse the daily patterns in the dendrometer data.

WP8 – Validating the climate interpolation model, part 2 – using data from dendrometer measurements

For the analysis of the dendrometer measurements, meteorological time series (temperature) based on each dendrometer sites were created using the INCA dataset and corrected with respect to elevation using the hourly lapse rates (rate at which atmospheric temperature decreases with an increase in altitude) derived from the INCA dataset. Every INCA grid-point from the catchment studied was taken on an hourly basis and a linear regression with the altitude of the grid-points was performed. The multiplicative term of the regression is the laps rate. These laps rates were used to interpolate the temperature to the altitude of the dendrometer plots. The comparison between temperatures measured at the dendrometers and predicted by INCA show systematic differences, that depend on the time of the year, location and exposition. This can be explained by the microclimate in the forests, different circulation regimes in the valleys and slopes, and different shading due to terrain. Fig. 3 show exemplary the difference between observed temperatures and INCA at Schlegeis for different expositions.

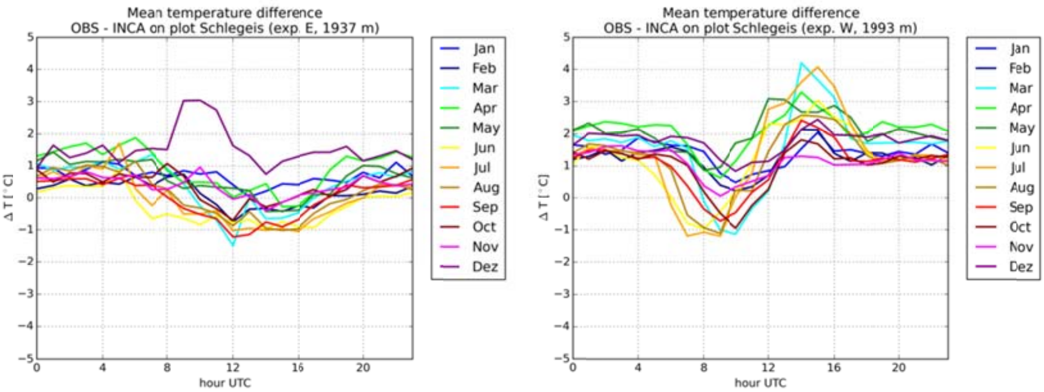


Fig. 13. Mean difference of temperature measured at dendromenters and predicted by INCA for the Site Schegeis with exposition to the East (left) and to the West (right).

Since dendrometers have got no radiation shield, it was necessary to get an estimate of the radiation error. This was done by comparing both dendrometers at a plot directly to each other. They generally show good agreement during times, when not affected by radiation, which is a sign of good accuracy. The differences are well below 0.5 °C. However during time of the day, when dendrometers are exposed to insolation large differences occur. As the position of the sun moves the dendrometers may receive direct sun light through a hole in the canopy. It is likely that only one dendrometer is exposed. To diminish the effect of radiation the measurements of both dendrometers were combined and only the minimum temperature at one time was taken for analysis. Fig. 4 the difference of temperature between two dendrometers at one plot at Zembachtal is shown. It shows clear dependency of the time of the year and time of the day.

Temperature lapse rates from the INCA dataset were compared to instrumental lapse rates from the dendrometers. It appears, that INCA assumes that the inversion is mixed earlier, than in reality, and the inversion is less pronounced in INCA during winter time. This may be explained by the lack of mountain stations in the study region. Another explanation may be the microclimate in the forest, since the dendrometers are no WMO conformal measurements in open space. In Fig. 5 lapsrates derived from INCA and dendrometer measurements are compared.

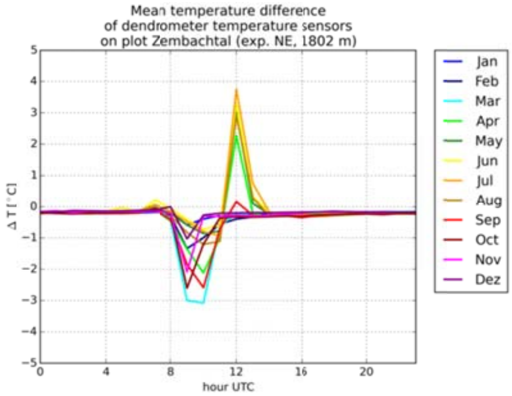


Fig. 14. Difference of temperature between two dendrometers at one plot at Zembachtal. Radiation errors as function of the time of the year and time of the day.

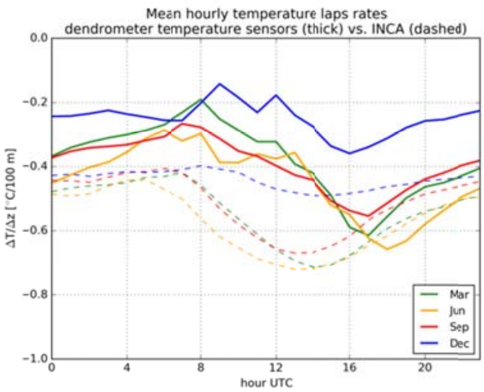


Fig. 15 Comparison of temperature laps rates derived from INCA (dashed) and dendromenter measurements (thick).

WP9 – Project management and administration

Project management and administration was done BOKU, Forest Growth. Sonja Vospernik and Renate Nistl were responsible for staff management, organizing meetings, travel organization and the coordination of joint publications. Kick-off meeting was on 20th/21st June 2012 (University of Innsbruck) followed by project meetings on 19th February 2013, 14th November 2013, 14th March 2014 in Vienna-University of Natural Resources and Life Sciences and on 27th February 2015 in Freiburg i. B.-University of Freiburg, Germany bringing together all project partners.

5 Conclusions and recommendations

(max. 5 Seiten)

Beschreibung der wesentlichen Projektergebnisse. Welche Schlussfolgerungen können daraus abgeleitet werden, welche Empfehlungen können gegeben werden?

The last decades of the last century and ongoing century were characterized by an increase of mean annual temperature since the 1980s and changing precipitation patterns. Trees are directly affected by these changes and a possible reaction would be increasing or decreasing growth rates. However, both inter- and intra-annual growth patterns a highly variable depending on tree species, age and site (elevation, soil type) and competition. Another important factor might be tree mixture. Therefore when analysing the influences of climate on tree growth it is important to taken into account these factors before drawing conclusions on the impact of climate change on trees. In our study Swiss pine shows partly a different behaviour than Norway spruce, but overall growth parameters, i.e. total ring width and latewood width, of both species prove enhanced growth during the last ca. three decades. Particularly important for the analysis of impact of climate change on tree growth are long-term datasets on a variety of sites. These complex datasets require careful statistical analysis. Complex modelling approaches in growth analysis allow for controlling for more than one independent variable, accommodating some of the complexity of the studied system.

Diameter growth occurs during a comparatively short period during the year. By sampling increment data at different elevations growth data can serve as proxy for climate data from the middle of April to the end of September. Climate predictions for impact studies should therefore focus on these months of the year. This is underlined by our results that show the highest correlations between latewood as well as combined tree-ring and latewood width series with temperature time series for the May to September season. The analysis of the regional effect of climate variability on tree rings, i.e. the temperature gradients in a mountain region, shows different sensitivity of the two species analysed. Based on into temperature data transferred the latewood data Swiss pine indicates a much lower whereas Norway spruce shows nearly the same gradient than expected from instrumental measurements.Long-term datasets for tree growth are very important, because of highly variable reactions patterns. BOKU Forest Growth, will therefore try to continue the monitor of tree growth in the project area.

This project also shows how important are meteorological stations in mountainous regions and at high altitude. Vertical characteristics of the atmosphere, like the depth and magnitude of inversions determine the temperature, humidity and wind at higher altitudes and therefore also influences the growth of the forests, among other areas of interest. However this cannot be measured from meteorological stations in the valley only, and assumptions for interpolation (like for INCA) have to be made.

C) Project details

6 Methods

(max. 10 Seiten)
Begründung und Darstellung des gewählten Forschungsansatzes.

Targets in this first project year were mainly to sample, measure and compile data from various sources (meteorological data, digital elevation map, stand data, tree ring data, dendrometer data) in order to obtain a clean data base for statistical analysis and the implementation of climate interpolation models (CIM) at the study region. Subsequently, the tree ring series and the simulated climate data were brought together to validate the climate interpolation model by investigating climate-growth-relationships, paying special attention to the key climate variables.

24 elevational transects were chosen near the barrier lakes Schlegeisspeicher and Durlassboden and in side valley near the lakes in the Ziller Valley in Tyrol. The altitude ranged between 1300 m and 2100 m, up to the tree line. On each transsect 9 – 12 sampling points were selected, where elevation, aspect, slope, geographic coordinates (latitude, longitude), micro relief, soil properties (water content, depth, group, humus, etc.), vegetation type and basal area were measured respectively assessed. The reasoning behind this strategy was to cover a wide range on altitude above the valley floor and different expositions and tree species.

In total, 438 Norway spruce and 252 Swiss pines were cored. Increment cores were taken from plots in approximately 34m ± 17m altitudinal steps by extracting 2 cores from opposite sides of the stem from 3-4 trees (one tree with mean basal area and 2-3 trees with dominant height) per sample plot at breast height (1.3 m above ground slope upwards) using a standard increment borer. For this study only dominant trees with healthy crowns (→ maximization of the climate signal, reduction of noise caused by disturbances) were cored.

Tree ring measurement (early-and latewood width) was carried out to the nearest 0.01 mm with standard measuring tables (LINTAB table and Johann´s Digitalpositiometer) and using TSAP-Win software (Rinntech). The raw data was checked for false or missing rings, synchronized, dated and standardized using the RCS-method (regional curve standardization.; e.g., Briffa and Melvin, 2011). Using these methods it was possible to construct a standardized time series on tree ring width for further analysis and as a supplement to existing chronologies.

On 56 plots dendrometers were installed, which measure the circumference of a tree plot at breast height (1.3 m above ground slope upwards) and also measure the air temperature on a hourly basis. Additional soil temperature loggers were dug in 10 cm depth near the instrumented trees, with a sample frequency of 3 hours (due to limitations in storage and beacause soil temperature reacts slowly). This was done to measure the response of trees to different weather conditions.

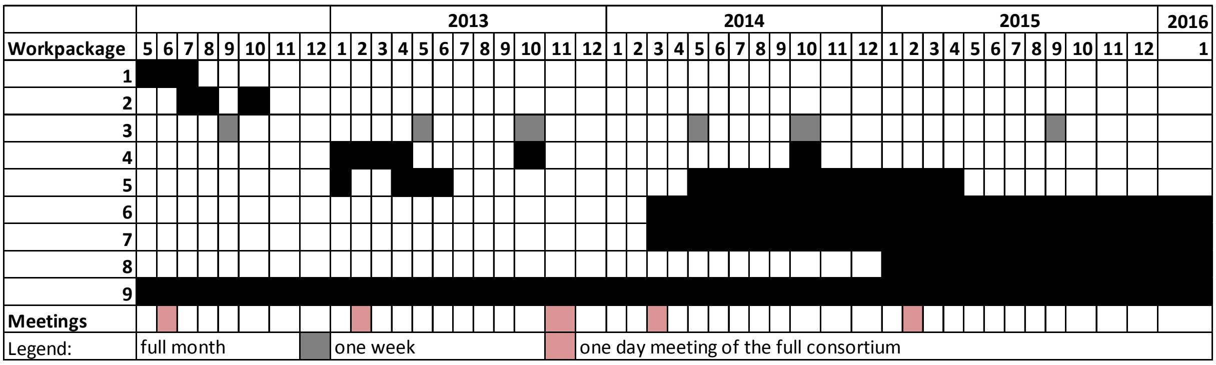
Meteorological data was obtained from nearby weather stations and gridded datasets (INCA, form 2003 and HISTALP, 1780 – 2008, both from ZAMG). Where applicable, the data was interpolated to the altitude of the plots by using laps rates (rate of change of a variable with altitude) derived from the data sets. The climate data was used for various statistical analysis.

Since the width of tree rings is not linear with the age of the tree, it is necessary to normalize the tree ring with. Different growth modes were applied to describe growth in a proper way. For a detailed view see WP6. Growth trends with altitude and exposition were evaluated using regressions. Response function analysis was applied to obtain most relevant climate elements, that determine tree growth (see WP 5). Modelling and analyses were performed with R-statistics using the lme4-package (Bates, Maechler, Bolker, & Walker, 2015), (R Core Team, 2015). A non-linear hierarchical mixed model was fit to the dendrometer data (for details see WP 7).

7 Work and time schedule

The following table gives an overview of the schedule of the projects work packages and consortium meetings. The work packages are coded from 1 – 9.

Tab 2 Work flow and packages



1. Increment coring and dendrometer installation
2. Tree-ring measurement
3. Inspection of the installes dendrometers and reading data
4. Data management and control
5. Validating the climate interpolation model, part 1 – using tree ring data
6. Growth trends in high elevation ecosystems of Norway spruce and Swiss pine
7. Hourly and intra-annual growth variation of Norway spruce and Swiss pine at high elevation sites
8. Validating the climate interpolation model, part 2 – using data from dendrometer measurements
9. Project management and administration

8 Publication and dissemination

SCI-Publications

Nicolussi K, Vospernik S, Pichler T, Weber G, Formayer H, Groff J, Leidinger D, Spiecker H, in preparation. Growth trends of *Picea abies* and *Pinus cembra* trees at altitudinal transects in the central eastern Alps and their relations to temperature gradients (in preparation, Oktober 2016). Theoretical and Applied Climatology.

Groff J., Vospernik S., Leidinger D., Nicolussi K. Growth trends in Norway spruce and Swiss pine in the 20th century: A mixed model approach Forest ecology and management

Vospernik, S., Nothdurft A.: Interannual growth variation of *Picea abies*, *Pinus cembra*, *Fagus sylvatica* from 2011- 2015 (in preparation, August 2016). Canadian Journal of Forest Research

Vospernik, S. Nothdurft, A.: Daily fluctuations of growth (working title). European Journal of Forest Growth Research

International and national conferences

Vospernik S., Pichler T., Leidinger D., Spiecker H., Formayer H., Nicolussi K., Motz, K. (2013) Validating a climate interpolation model using tree ring data from the Austrian Central Alps. ClimTree, Zürich, Switzerland, 1-5th September 2013

Vospernik S., Nicolussi K., Leidinger D., Formayer H., Pichler T., Groff J., Spiecker H. (2014): Analyse der Beziehung von Waldwachstum und Klima bei Fichte und Zirbe an Seehöhengradienten in Tirol (Analysis of forest growth and climate for Norway spruce and Stone pine at altitudinal gradients in Tyrol). Klimatag. April 4th 2014, Innsbruck

Vospernik S., Nicolussi K., Groff J., Pichler T., Spiecker H. (2014): Waldwachstum und Klima bei Fichte und Zirbe an Seehöhengradienten in Tirol (Forest Growth and Climate in Norway spruce and Swiss pine on altitudinal gradients in Tyrol).
Sektion Ertragskunde (2-4. June 2014, Lenzen a. d. Elbe, Germany).

Nicolussi K., Vospernik S., Pichler T., Formayer H., Groff J., Leidinger D., Spiecker H. (2014): Growth trends of *Picea abies* and *Pinus cembra* trees at altitudinal transects in the central Alps. EuroDendro 2014 (8-12. September 2014, Lugo, Spain),

Nicolussi K., Vospernik S., Pichler T., Formayer H., Groff J., Leidinger D., Spiecker H. (2015): Reaktion des Jahrringzuwachses von Fichten und Zirben an Höhentransekten in den zentralen Ostalpen auf den gegenwärtigen Klimawandel.
16. Österreichischer Klimatag, 28.-30. April 2015, Wien.

Leidinger D., Formayer H., Vospernik S., Groff J., Nicolussi K., Spiecker H. (2015)
ICAM (Int. Conference on Alpine Meteorology, 31st August – 4th September 2015, Innsbruck): Monitoring tree growth in alpine regions in Tyrol.

Vospernik, S., Nothdurft, A. (accepted): Inter-annueller Zuwachs von Fichte, Buche und Zirbe. (Inter-annual growth variation of Norway spruce, Common beech and Stone pine.).
Sektion Ertragskunde 2016. 8-11 May 2016, Lyss, Switzerland

Presentations for stakeholders

Vospernik, S., Motz, K.: 2013: Kurzpräsentation ClimInterVal für den Klimatag der Öbf-AG. (Short presentation of ClimInterVal for climate day of the Austrian Federal Forests).

Planned: Presentation of project results for Austrian Federal Forests.