

ÖAW-ESS-Project

ClimLUC – Climate extremes and land-use change: effects on ecosystem processes and services

Final Report, December 2018

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1. Executive summary

An increase in extreme drought events due to global climatic change is predicted to have a significant impact on ecosystem health and the provision of ecosystem services over the next century. However, there is a large uncertainty regarding non-linearity and thresholds in ecosystem responses to such extreme events. In addition, the effects of extreme drought may alter ecosystem functioning beyond immediate responses, inducing legacy effects which modulate future resilience. Current models do not adequately represent non-linear threshold and legacy effects in response to extreme events, thus there is an urgent need to explicitly test and quantify these features to gain a mechanistic understanding and improve model predictions. Responses to drought may furthermore be modulated by socioeconomic factors such as changing land use, which is particularly prominent in alpine regions. The ClimLUC project therefore aimed to understand how extreme summer drought affects the carbon and water dynamics of mountain ecosystems under different land uses, and by extension the provisioning of ecosystem services, using a combination of experimental and modelling approaches.

Work package 1 "*Ecosystem processes and ecophysiology*" focused on drought responses from across three different land use types: Managed and abandoned mountain grasslands, as well as a subalpine forest. A major achievement of this WP was the establishment of a new forest subsite at the LTSER-Master site Stubai. The results of WP1 showed that abandonment of managed grassland reduced greenhouse gas fluxes and affected microbial functional gene abundances and plant tissue stoichiometry. Resistance of productivity, ecosystem carbon dynamics and plant-soil interactions to drought was higher for abandoned, compared to managed grassland, however recovery from drought stress was slower. Dendroecological analyses of the main tree species Norway spruce and European larch along elevational gradients on South- and North-facing slopes suggest that, during the past century, tree growth was barely impacted by water limitation. The drought experiments, however, indicated that more extreme droughts possibly occurring in the coming decades, can cause significant reductions in radial growth, especially for spruce. Surprisingly, both in the grasslands and in the subalpine forest, drought reduced productivity more strongly than water losses and therefore led to consistent reductions in water use efficiency across all sites. Drought legacies increased the vulnerability of ecosystem processes to subsequent drought. This was particularly evident on the managed grassland exposed to ten years of subsequent drought, and calls for follow-up research to unravel the underlying causes and the consequences of effects more frequent drought events in a future climate.

The major objective of work package 2 "*Ecosystem modelling*" was to understand how the ecosystem model ORCHIDEE represents the effects of changes in climate, including precipitation, on ecosystem CO₂ and water fluxes, as well as productivity, using climate and ecosystem data from the Stubai study site. The simulations showed that modelled productivity had a strongly nonlinear response to precipitation reduction, with productivity decreasing sharply once a threshold reduction was reached. This was

particularly evident for forest ecosystems. Comparison to observations showed that the model could reproduce drought responses well, however recovery was underestimated by the model. Simulations for future climate by the end of the century suggested that increasing temperature can counteract the reduction in productivity induced by drought for some ecosystems.

Work package 3 "*Ecosystem services*" aimed to 1) quantify the provision of ecosystem services in the Stubai valley compared to land use and management changes as well as the occurrence of extreme events for historical data, to guide predictions of future activity, and 2) to assess the relative importance of climate, management and natural disturbances for forest ecosystem services. The results did not show strong evidence of systematic linkages between extreme events and land use shifts on long timescales in the past. This may be due to the low temporal resolution of spatially explicit land cover data, compared to the dynamic nature of extreme events. In addition, societies have developed resilience in management and ecosystem use over time, which may have buffered the effect of extreme events. Thus, the identification of tipping points and transition phases in land use and management is key for future research in this area.

Overall, the ClimLUC project indicates that, in the Stubai Valley, the comparatively rare and mild drought events during the last century had only minor implications for ecosystem process and the provisioning of ecosystem services. However, the likely occurrence of more severe and more frequent droughts, suggested by climate projections, can lead to significant reductions of the productivity and of water use efficiency across managed and abandoned grassland and forests. While drought resistance generally increased from managed to abandoned grassland, and was higher for larch than for spruce, recovery processes may follow opposite patterns, and consequences of drought legacies may increase overall vulnerabilities. Implications for pest outbreaks and fire risk were not studied here, but may further decrease the resilience of mountain ecosystems in a future climate. Adaptation measures of socio-ecological systems to such compound and legacy effects will be essential for ensuring the provisioning of ecosystem services of mountain ecosystems under future climate conditions.

2. Introduction

Recent climate projections suggest that extreme climatic events, such as severe droughts, heat waves, exceptional frosts, extreme precipitation and storms, will increase in frequency and severity during the coming decades (IPCC 2012). Extreme climatic events may affect biogeochemical cycles, ecosystem services and socioeconomic systems more strongly and rapidly than gradual climate changes (e.g. Schär et al. 2004, Jentsch et al. 2007, Soussana et al. 2010, Schwalm et al. 2012, Frank et al. 2015). It has been suggested that, by the end of the century, events that are considered extreme today will be in the range of typical interannual climate variability, while the severity and frequency of events of a given return interval will increase (Smith 2011, IPCC 2012, Williams et al. 2013). Such highly severe extreme climatic events may result in the crossing of thresholds of plant and ecosystem functioning, as recently observed in some forest ecosystems (Allen et al. 2010, Anderegg et al. 2012). Globally, droughts and heatwaves are the climate extremes exerting the largest effect on the carbon (C) cycle and related processes (Reichstein et al. 2013). Extreme drought can take plants beyond their hydraulic safety margins (Choat 2013, Klein et al. 2014) and cause substantial reductions in ecosystem productivity and C sequestration (Ciais et al. 2005, Zscheischler et al. 2013). Drought also typically impacts on ecosystem water use (Reichstein et al. 2007, Zha et al. 2010), with consequences for water conservation and thus catchment and river discharge (Schwalm et al. 2012). While much has been learned about effects of extreme climatic events based on recent observations and experiments, there is still a large uncertainty on the threshold responses of ecosystem processes and their effects on the provisioning of ecosystem services to future, increasingly severe and frequent climate extremes (McDowell et al. 2013, Bahn et al. 2014, Schwalm et al. 2017).

Extreme climatic events not only have concurrent effects on ecosystems, but may also induce legacy effects altering ecosystem functioning beyond the immediate responses (Reichstein et al. 2013). It is well known that tree growth is often reduced not only during drought events but also in the subsequent year and beyond (LeBlanc & Foster 1992, Babst et al. 2013, Anderegg et al. 2015). Similarly, tree mortality may be increased one or more years after the occurrence of extreme drought (Bigler et al. 2007, Bond-Lamberty et al. 2014). Rewetting after drought has been shown to cause large peaks of mineralization, resulting in substantially enhanced soil CO₂ emissions (Borken & Matzner 2009, Kim et al. 2012), potentially leading to reductions in ecosystem and soil C sequestration (Jarvis et al. 2007, Muhr & Borken 2009a, Goeransson et al. 2013). Legacy effects may also change the response of ecosystem processes to subsequent extremes (Muhr et al. 2009b, Walter et al. 2013). For example, there is emerging evidence that extreme drought may alter the response of productivity, carbon allocation dynamics and soil CO₂ emissions to subsequent drought (Barbeta et al. 2013, Kopittke et al. 2014, Vicca et al. 2014, Fuchslueger et al. 2016). Current Dynamic Global Vegetation Models and Earth System Models do not sufficiently account for threshold and legacy effects of extreme climatic events, which may be critical for projections

of climate–biosphere interactions in a more extreme world (McDowell et al. 2011, Reichstein et al. 2013, Bahn et al. 2014, Refsgaard et al. 2014). For gaining realistic response functions based on a mechanistic understanding of plant and ecosystem responses to extreme climatic events there is an urgent need for experiments explicitly testing for threshold responses and legacy effects (Beier et al. 2012, Reyer et al. 2013, Kreyling et al. 2014).

Land use and its change over time acts as a further important driver of global change besides climate change. Changes in land use and management have been occurring widely across many mountain areas of Europe, most prominently intensification and abandonment of grasslands, as well as reforestation (Tappeiner et al. 2003, Tasser et al. 2007), with far reaching effects for ecological processes (Leitinger et al. 2010, Schmitt et al. 2010, Meyer et al. 2012) and ecosystem services, such as the provisioning of food and feed, water purification, carbon storage or cultural services (Tappeiner et al. 2008, Schirpke et al. 2012, Erb et al. 2013). Although land use may be affected by climate change, the interactive effects of land-use and climate change on ecosystem functioning have so far not been well studied (Gill 2014, Oliver & Morecroft 2014). Globally, there is a lack of comparative studies indicating how climate extremes affect ecosystem processes and services under different land management and land use (Bahn et al. 2014), and how these are coupled with society's demands and responses. Land-use induced land-cover changes and shifts in plant functional types, e.g. caused by abandonment of grassland leading to regrowth of forest, may buffer or amplify effects of climate changes with increasing severity of extreme climatic events, and may thereby induce very different response trajectories in ecosystems: under drought / heatwaves forests have been suggested to follow a more conservative water use than grasslands (Teuling et al. 2010), often leading to higher water-use efficiencies of primary productivity (Wolf et al. 2013). While grasslands are thus more rapidly and severely affected by drought and heat waves (Teuling et al. 2010, Zha et al. 2010), the speed and degree of their recovery from such an extreme climatic event could be higher, though this has not yet been consistently shown (Wolf et al. 2013). Also legacy effects (cf. above) may differ between ecosystems differing in land use (Shi et al. 2014) and could eventually also result in changed patterns and magnitudes of ecosystem services provisioning and trigger the development of future land uses, e.g. by altered management practices, response to fire risk and the perception of recreational and thus touristic value. However, as previous studies comparing drought responses of grassland and forest were purely observational, we still lack consistent information on threshold responses and legacy effects of extremely severe drought, whose future probability of occurrence is expected to increase significantly, on ecosystems differing in land use and how this will affect land use decisions and land use change.

The overarching objective of the ClimLUC project was to understand how extreme summer drought affects carbon and water dynamics of mountain ecosystems under different land uses, and to analyse implications for ecosystem service provisioning.

The specific objectives of the ClimLUC project were

- 1) to test experimentally how (a) a managed, (b) an abandoned mountain grassland and (c) a (newly established) adjacent subalpine forest respond to a progressive extreme drought and to analyse threshold responses of carbon and water dynamics and their implications for ecosystem services;
- 2) to quantify carry-over effects of the extreme event on ecosystem processes and services;
- 3) to project and attribute future carbon and water cycle responses to extreme drought and related socio-economic changes;
- 4) to analyse the interrelation between land-use changes and the occurrence and severity of past and future extreme events and to identify their individual and combined effects on the provisioning of ecosystem services;
- 5) to identify management options that allow increasing the resilience of the socio-ecological system to climate extremes.

The overarching hypothesis was that land-use change alters the effects of extreme summer drought on ecosystem processes and the related services. Specifically, the following hypotheses were tested:

H1 Drought impact (resistance): Under extreme drought water conservation and water use efficiency increase from managed to abandoned grassland and forest, which decreases the severity of drought impacts on productivity, soil and ecosystem carbon dynamics and ecosystem water loss.

H2 Drought recovery: The recovery of ecosystem productivity after extreme drought decreases from managed to abandoned grassland and forest.

H3 Landscape scale attribution: Extreme drought has more pronounced consequences for the landscape scale carbon cycle than gradual climate changes, but the degree of influence depends on the frequency of extreme climatic events and their effect on land management and land-use change.

H4 Ecosystem service provisioning: By affecting the provisioning of ecosystem services, extreme climatic events are important drivers of land-use change.

The proposed study was located at the LTSER (long term socio-ecological research) site Stubai Valley, a master site of the LTSER platform Tyrolean Alps (Tappeiner et al. 2013). Since the mid 1990ies the site has been studied intensely in a number of national (FWF, TWF, ao.) and international research projects (EU-FP 4,5,7, including FP7 projects Carbo-Extreme and GHG Europe; ERA-Net projects VITAL and REGARDS). The ClimLUC project built on the previous projects immediately related to the proposed work, especially the ones addressing effects of land-use changes in grasslands and effects of severe drought events on grassland carbon dynamics. ClimLUC permitted working up and publishing already available datasets from these projects, yielding several publications in highly ranked international journals (Harris et al. 2018, Hörtnagl et al. 2018, Ingrisch et al. 2018, Karlowsky et al. 2018a,b, Szukics et

al. 2019). ClimLUC permitted developing and testing a framework for a comparable quantification of resilience, required for comparisons across different ecosystems and ecosystem processes, which was published in the leading journal in the field of ecology (Ingrisch & Bahn 2018, Bahn & Ingrisch 2018). Furthermore, ClimLUC significantly extended beyond the previous projects by establishing a new site at a subalpine forest, and an adjacent abandoned grassland site, permitting the analysis of consequences of land-cover changes following the abandonment of mountain grassland (including shrub encroachment and reforestation) for drought responses of mountain ecosystems (Anadon-Rosell et al. 2017, Stuart-Haëntjens et al. 2018, Oberleitner et al., in prep., Ingrisch et al., in prep, Bahn et al. in prep.). The ClimLUC project also used the opportunity to combine emerging results from the experimental studies with available landscape-scale information on past and present vegetation cover dynamics and climate conditions, as well as future climate and land-use scenarios to expand from the ecosystem scale to the Stubai Valley as a whole, using state-of-the art modelling (Niedertscheider et al. 2017, Tasser et al. 2017, Wu et al. 2018, Seidl et al., in prep.).

The proposed work was allocated to three major work packages (WP), which were broadly related as depicted in Fig. 1.

WP 1: Ecosystem processes and ecophysiology, aiming to experimentally test and analyse effects of extreme drought on plant and ecosystem responses in a managed and an abandoned mountain grassland and an adjacent subalpine forest

WP 2: Ecosystem modelling, aiming to integrate, upscale and project ecosystem CO₂ and water vapour fluxes and to attribute effects of extreme drought versus those related to gradual climate change and land-use change on the respective landscape scale fluxes

WP 3: Ecosystem services, aiming to analyse the interrelation between land-use change and extreme climatic events and to identify their effects on the provisioning of ecosystem services, as well as management options

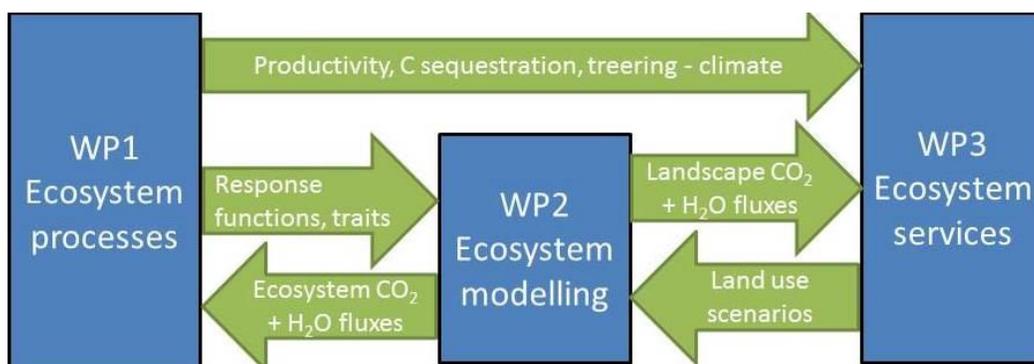


Figure 1: The three workpackages of ClimLUC and their linkages.

3. Ecosystem processes and ecophysiology (Work Package 1)

Michael Bahn, Roland Hasibeder, Florian Oberleitner, Walter Oberhuber, Johannes Ingrisich, Henrik Hartmann, Eliza Harris, Stefan Mayr, Rupert Seidl, Gerhard Wieser, Ursula Peintner, Kevin Van Sundert, Sara Vicca & the ClimLUC student team (* see cover page and list of theses)*

3.1 Overview of work performed

Work Package 1 aimed to understand how land-use changes affect the drought responses of plant and ecosystem processes. Next to establishing background effects of land-use changes and climate variability on grassland processes (chapter 3.1) and tree radial growth (chapter 3.3), respectively, the core objective was to perform a series of drought experiments in a managed and an abandoned mountain grassland (chapter 3.2) and an adjacent subalpine forest (chapter 3.4).

Table 1 provides an overview of the rain-out experiments in relation to growing season precipitation. Fig. 2 summarizes the experimental design of the *in-situ* experiments, while Fig. 3 provides some visual impressions of the experiments. Fig. 4 and Fig. 5 provide an overview of the microclimatic conditions during the study years. Fig. 5 illustrates that the rain-out treatments led to significant reductions in soil moisture across all sites, the effects declining with soil depth and from managed to abandoned grassland and the subalpine forest.

Land-use type	Year	Rainout period	Growing season precipitation	Precipitation excluded	% of precipitation excluded
Meadow	2016	15.06. – 16.08.	873	426	49
	2017	17.05. -01.08.	1206	417	35
	2018	07.06. – 06.08.	617	201	33
Abandoned grassland	2016	16.06. – 18.08.	873	421	48
	2017	18.05. – 03.08.	1206	426	35
	2018	no experiment performed on abandoned grassland in 2018			
Forest	2016	10.07. – 21.09.	873	411	47
	2017	10.05. – 27.09.	1206	1045	87
	2018	31.05. – 26.09.	617	460	75

Table 1: Rainout periods, sum of precipitation during the growing season and the amount of precipitation excluded by the rainout treatment during the growing season (15 April - 15 October) for the study years 2016, 2017 and 2018.

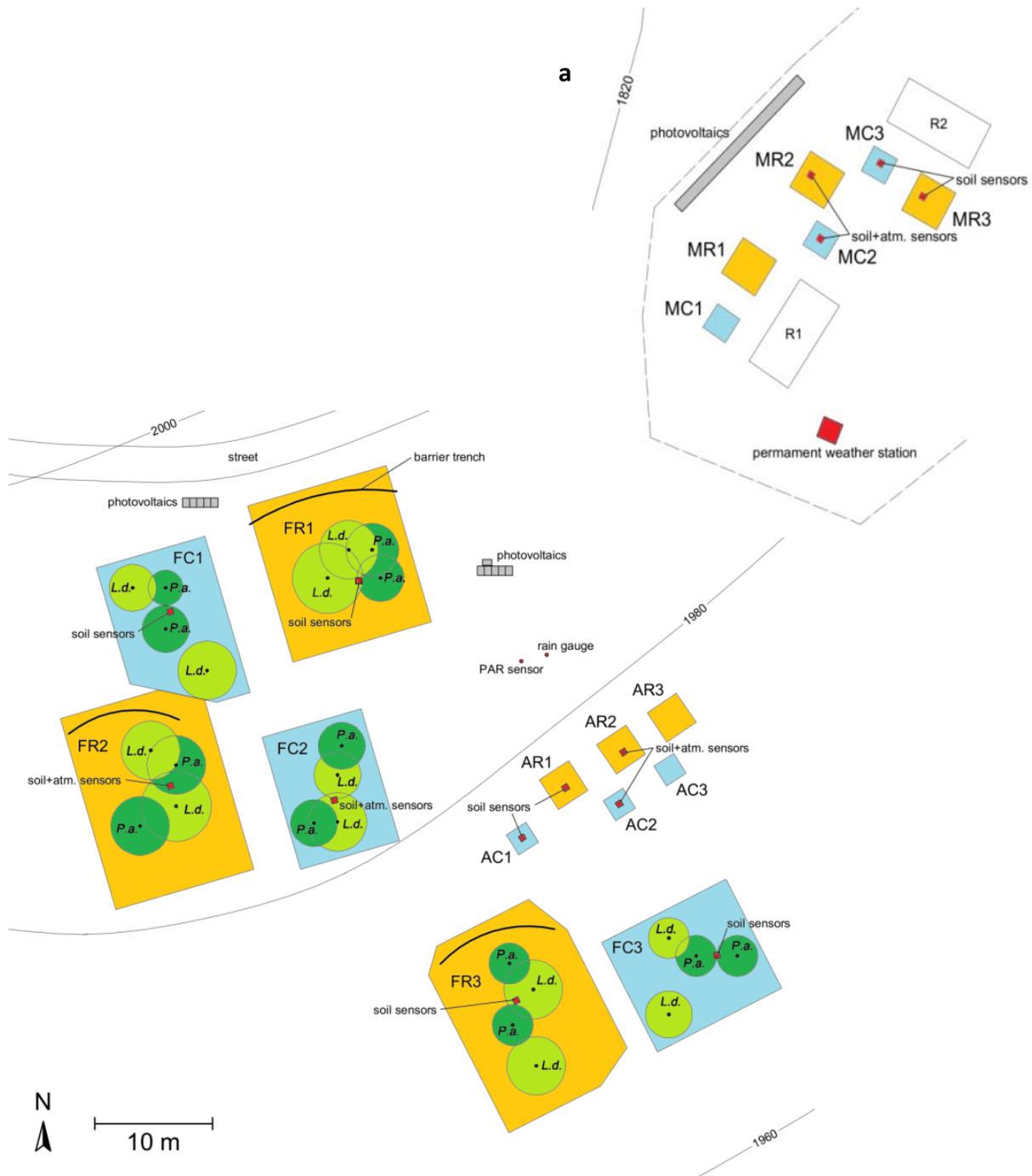


Figure 2: (a) Layout of the meadow site, showing the arrangement of 3 drought plots (MR1–3, orange) and associated control plots (MC1–3, blue) in 2017, and the locations of microclimate sensors, permanent weather station and photovoltaic power supply. The plots R1 and R2 are part of an ongoing long-term experiment. (b) Layout of the mature forest site (drought plots FR1–3, orange; control plots FC1–3, blue) and the adjacent abandoned grassland site (drought plots AR1–3, orange; control plots AC1–3, blue), including the locations of microclimate sensors and photovoltaic power supplies. Within the forest site plots the trees equipped with dendrometers and sap flow sensors are indicated by *L.d.* (*Larix decidua*) and *P.a.* (*Picea abies*).

a



b



c



d



Figure 3: Rain-out experiments at (a) meadow, (b) abandoned grassland and (c, d) forest site.

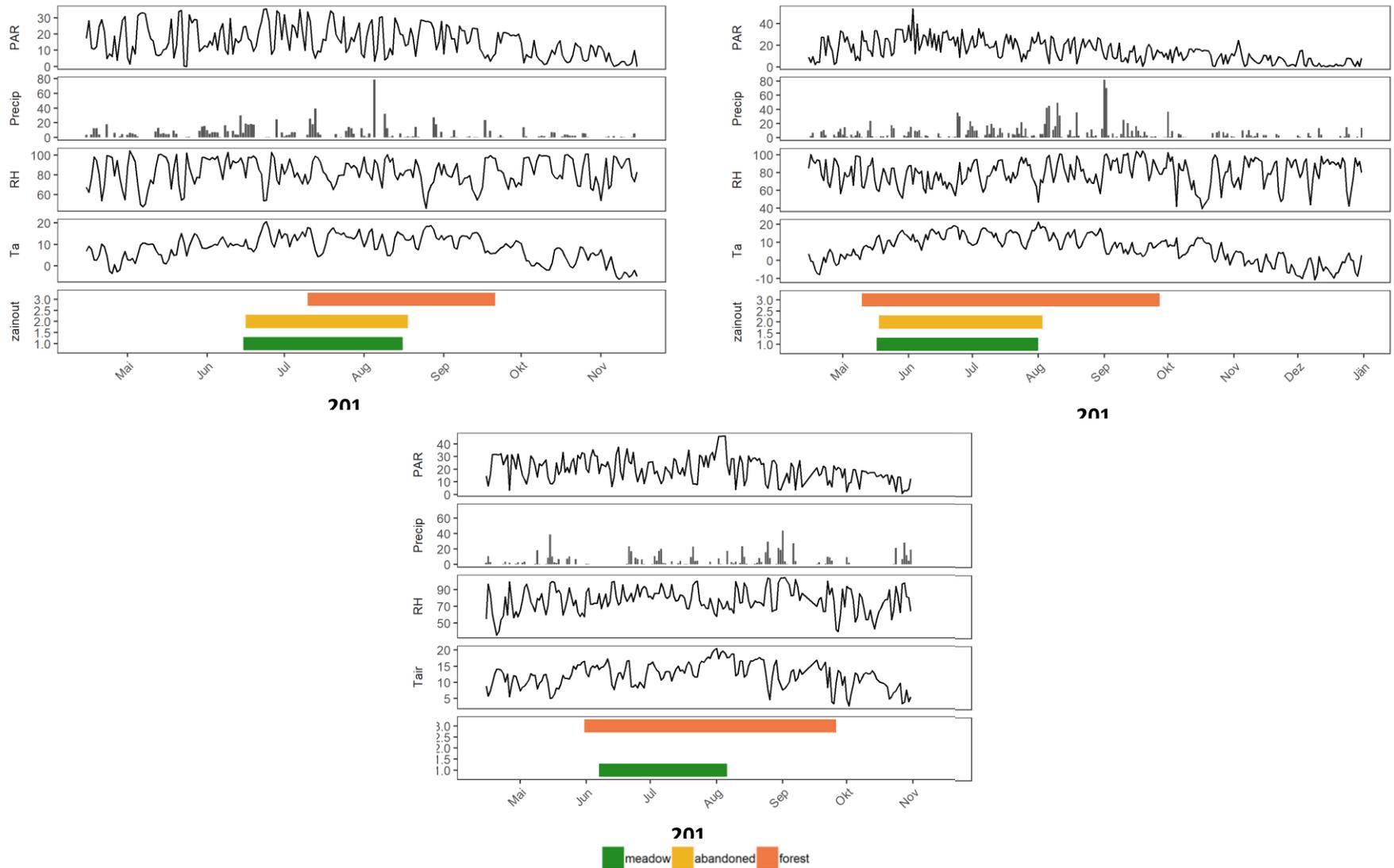


Figure 4: Seasonal dynamics of photosynthetically active radiation (PAR, $\text{mol m}^{-2} \text{d}^{-1}$), precipitation (Precip, mm), relative humidity (RH, %) and ambient temperature (T_{air} , $^{\circ}\text{C}$) during the years when the drought experiments were performed. Coloured bars denote rainout periods.

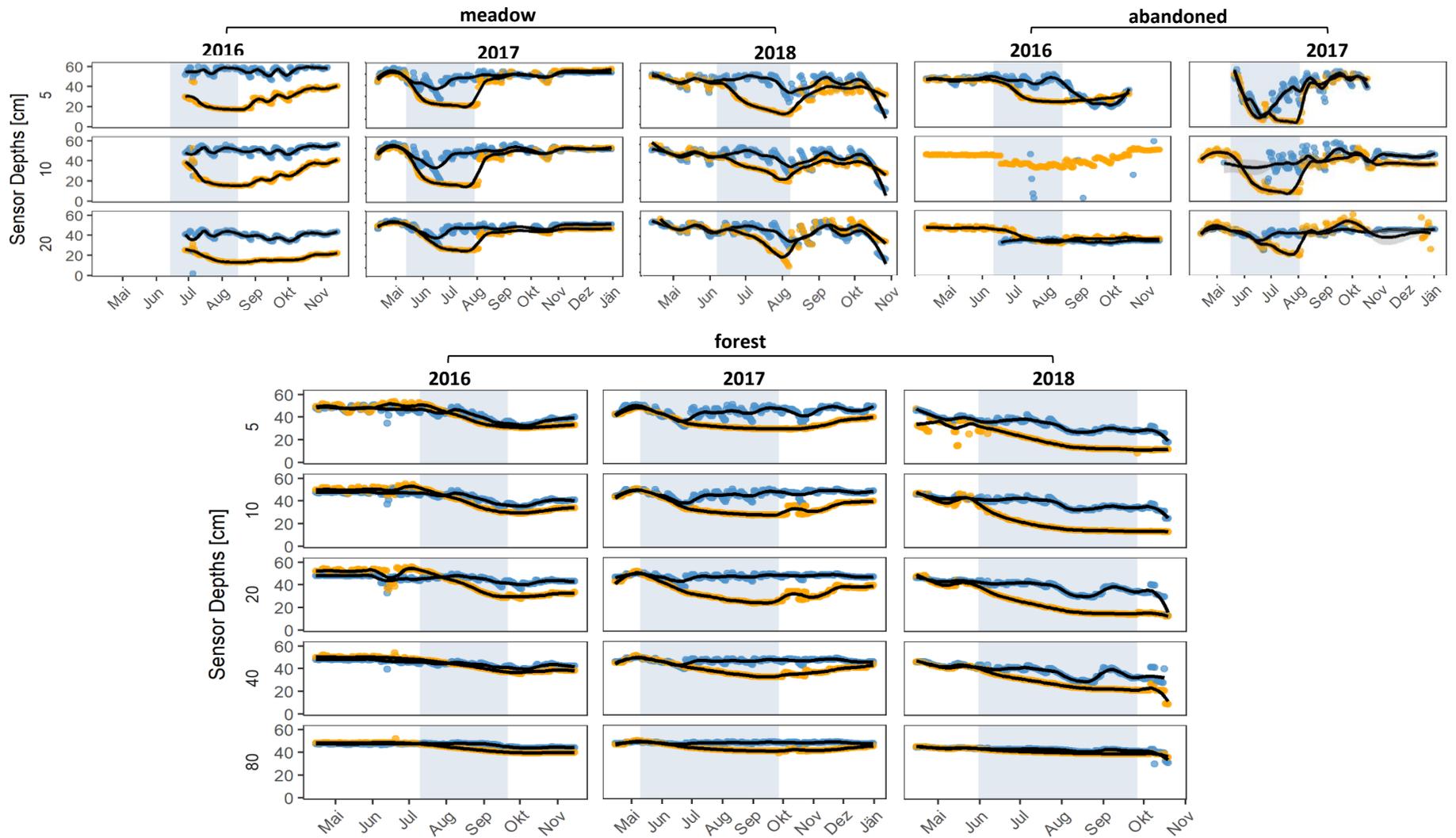


Figure 5: Seasonal dynamics of soil water content (%) across the soil profile at the meadow, abandoned grassland and forest site. Blue colour denotes control treatment, orange colour denotes drought treatment.

3.2 Effects of land-use changes on plant, soil and ecosystem processes in mountain grassland

European mountain grasslands have been managed for centuries, though in recent decades, socio-economic changes have led to abandonment of mountain meadows and pastures (Tasser et al. 2007). Abandonment alters the plant-species composition (Tasser & Tappeiner 2002), productivity and CO₂ fluxes (Bahn et al. 2006, Schmitt et al. 2010), soil organic matter dynamics (Meyer et al. 2012), the nitrogen cycle (Grigulis et al. 2013, Fuchslueger et al. 2014, Legay et al. 2014) and the water cycle (Obojes et al. 2015). The ClimLUC project permitted the publication of previously measured datasets on the nitrogen cycle and greenhouse gas fluxes. A detailed analysis of the abundance of functional genes driving the nitrogen cycle revealed, that across European transects site-specific conditions and the type of management, but not its intensity, determined the abundances of nitrogen (N) transforming microbes, contrasting findings from lowland grasslands which indicate a strong influence of land use intensity (Szukics et al. 2019). Non-CO₂-greenhouse gas fluxes in subalpine mountain grasslands were found to be amongst the lowest observed in Central Europe (Hörtnagl et al. 2018), abandonment even shifting grassland from net sources to small net sinks for nitrous oxide and methane (Harris et al. 2018). In spite of the comparatively small fluxes, these findings demonstrate the importance of non-CO₂ greenhouse gases in determining the net climate effect of land use changes, and the particular role of grassland abandonment, highlighting the need for a detailed understanding of fluxes to plan effective management and greenhouse gas mitigation strategies (Harris et al. 2018).

3.3 Drought effects on managed and abandoned grassland

A central aim of the project was to study the effects of grassland abandonment on the resilience of C dynamics against extreme summer drought. Since an ecosystem's resilience is composed of its resistance to a disturbance as well its ability to recover from disturbance (Ingrisch and Bahn 2018), we addressed drought effects on ecosystem functioning during, as well as after an extreme summer drought.

The overarching research questions were

- (1) How does grassland abandonment alter the resistance to and recovery from an extreme summer drought?
- (2) Can we identify mechanisms and ecosystem attributes underpinning grassland resistance and recovery?

To approach these questions, we performed a series of consecutive experiments: (i) a controlled common-garden experiment with soil-vegetation monoliths from two differently managed mountain grasslands and (ii) an in situ experiment at the two grassland-sites. We measured a range of ecosystem processes related to the biogeochemical cycles, in particular the C cycle, in order to quantify the

consequences of drought on grasslands and to understand the mechanisms underpinning grassland resilience.

The first experiment addressed the resilience of C dynamics in the two grasslands and the underpinning mechanisms. We chose a common garden design to maximise the comparability of the grasslands' responses by having similar environmental conditions. We measured the response of productivity, gross-primary productivity, and ecosystem respiration over the whole course of the experimental season. To identify mechanisms underpinning grassland resilience, we additionally performed two $^{13}\text{CO}_2$ pulse labelling campaigns during peak drought and recovery, respectively, and a $^{15}\text{NO}_3$ pulse labelling. This allowed us to analyse C allocation patterns within the plant-soil-atmosphere system and study the role of N for grassland recovery.

The second experiment aimed to study resilience of the two grasslands under undisturbed *in situ* conditions. Furthermore, we studied a broader range of response parameters by including soil respiration, belowground productivity and root traits, leaf stoichiometry and water fluxes.

In both experiments, drought was simulated experimentally with rain-out shelters, thereby excluding any precipitation for a period of several weeks. We studied gross primary productivity (GPP), ecosystem respiration and evapotranspiration using closed dynamic chambers (Ingrisch et al. 2018). Soil respiration was measured periodically with a EGM-4 (PP-Systems). Aboveground productivity, leaf traits and leaf stoichiometry were measured based on aboveground biomass sampling during peak drought. Root productivity and root traits were measured based on ingrowth-cores.

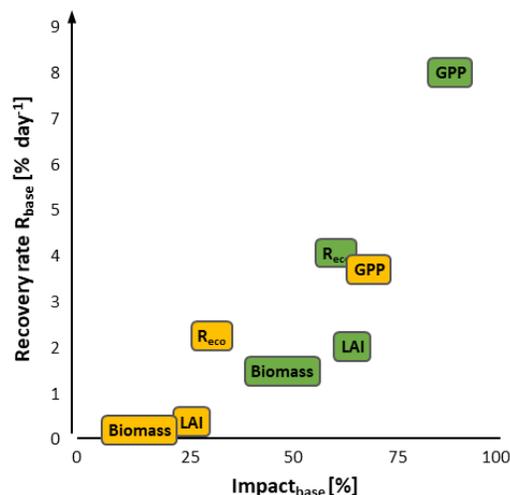


Figure 6: Bivariate representation of the resilience of the meadow (green) and the abandoned (orange) grassland in response to drought during the common garden experiment. Data from Ingrisch et al. (2018), modified according to Ingrisch & Bahn (2018). GPP = gross primary productivity, Reco = ecosystem respiration, LAI = leaf-area index.

We found that both grasslands studied here were highly resilient to drought (Ingrisch et al. 2018), though the contributions of resistance and recovery to the overall drought response were altered considerably by abandonment. The abandoned grassland showed a higher resistance of CO₂ fluxes, biomass and leaf-area index, and the managed grassland displayed clearly higher recovery rates (Fig. 6). This pattern clearly emerged from the common garden experiment (published in Ingrisch et al. 2018) as well as from the *in situ* campaign (Fig. 7-9). Drought responses were less pronounced in mid-summer than in early summer, and differed between years. In 2017 effects of mid-summer drought caused the most significant reduction of aboveground net primary productivity on the meadow, which was mainly due to a reduction of forbs, rather than grasses (Fig. 7). Drought events, which were repeated on the managed grassland for several subsequent years did not result in a change of the precipitation-productivity relationship (Estiarte et al. 2016), but exacerbated the shifts in functional groups in favor of graminoids, and led to legacy effects on root biomass production, mycorrhizal length and soil respiration and its rewetting responses (Bahn et al., in prep.).

In both managed and abandoned grassland, drought reduced soil respiration (Fig. 8, Ingrisch et al., in prep). The size of the 'Birch-effect', i.e. the pulse of soil CO₂ efflux upon rewetting after drought, has been suggested as an indicator for the severity and impact of a drought and was considerably larger in the meadow compared to the abandoned grassland (Fig. 8 a,c, Brune 2018), thereby providing further evidence for the higher drought-resistance of the abandoned grassland plant-microbial community. Overall, the Birch effect was more pronounced on the grasslands compared to the forest, reflecting the comparatively larger declines in soil moisture during the rainout treatments (Fig. 5).

During drought evapotranspiration (ET) was reduced in both managed and abandoned grasslands (Fig. 9 e,f). As a consequence of a higher drought impact on gross primary productivity (GPP) compared to ET, the water-use efficiency (WUE) declined under drought (Fig. 9 g,h), the effects being enhanced under recurrent drought (Bahn et al., in prep.). Similarly, drought impacts on C allocation and plant-microbial interactions were generally higher in the managed than in the abandoned grassland (Karlowsky et al. 2018).

We were able to identify a number of grassland characteristics and mechanisms, which drove resilience to drought and its interaction with grassland management. The higher resistance of the abandoned grassland was related to its more 'conservative' plant-functional composition, associated with the slow end in the fast-slow plant economic spectrum (Grigulis et al. 2013). Plants with a conservative strategy have leaf traits, which promote drought tolerance. Furthermore, we found that the abandoned grassland maintains a larger rooting network and a close association with mycorrhizal fungi under drought (Karlowsky et al. 2018). Plant-fungal coupling enhances drought resistance by improving the plant's access to water in soils (deVries et al. 2012, Fuchslueger et al. 2014).

In contrast, the managed grassland is adapted to frequent management (mowing), which favors species with an 'exploitative' strategy. Such plants can grow quickly and utilize available resources rapidly. These attributes are advantageous also for drought recovery. Additionally, we found evidence that post-drought nitrogen dynamics are enhanced in the managed compared to the abandoned grassland. Furthermore, the ability to use these nutrients is higher with management, which further improves post-drought recovery rates (Ingrisch et al. 2018, Karlowsky et al. 2018).

Expanding the nutrient spectrum to include also other nutrients, we also observed increased foliar phosphorous (P) concentrations after recovery from drought (Morcote-Martinez, in prep.) and an increased mobilisation on potassium (K) in soil during rewetting, which was particularly pronounced on the abandoned grassland, but resulted in significantly increased leaf K concentrations only the meadow (Van Sundert et al., in prep.).

Overall, the results from the grassland experiments highlight the essential role of the plants' position in the resource economic spectrum, of plant-soil interactions and of nutrient availability for the stability of grasslands to extreme drought. Complementary analyses suggest that, in addition, background climatic conditions (Wu et al. 2018, see also WP2) and multiple facets of biodiversity (Craven et al. 2018) are important extrinsic and intrinsic drivers of grassland responses to alterations in water availability, including drought stress.

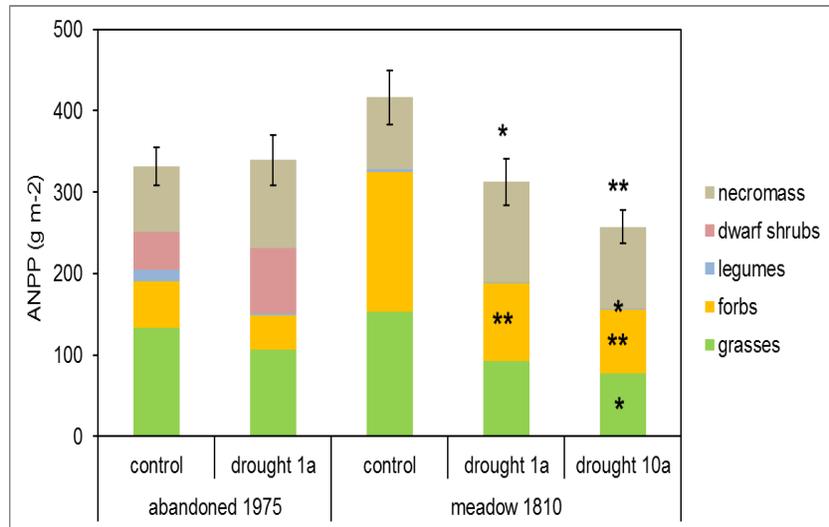


Figure 7: Mean aboveground biomass, sampled during the peak drought in 2017 in the abandoned and managed grassland in control and drought-treated plots (1a and 10a denote first and tenth year of consecutive drought). Colors denote functional groups and necromass.

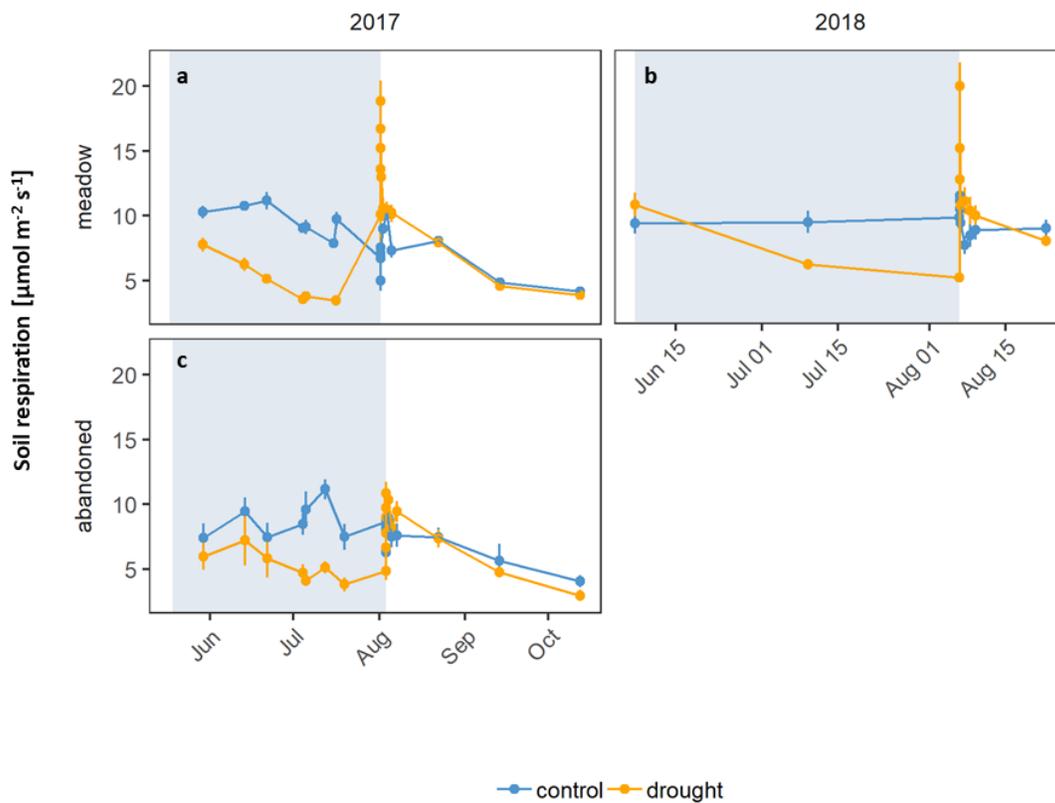


Figure 8: Seasonal course of soil respiration in (a, b) the meadow and (c) the abandoned grassland in the experimental years of 2017 (left) and 2018 (right). Color denotes the drought treatment, error bars \pm SE. Shaded area indicates the time of rain-exclusion.

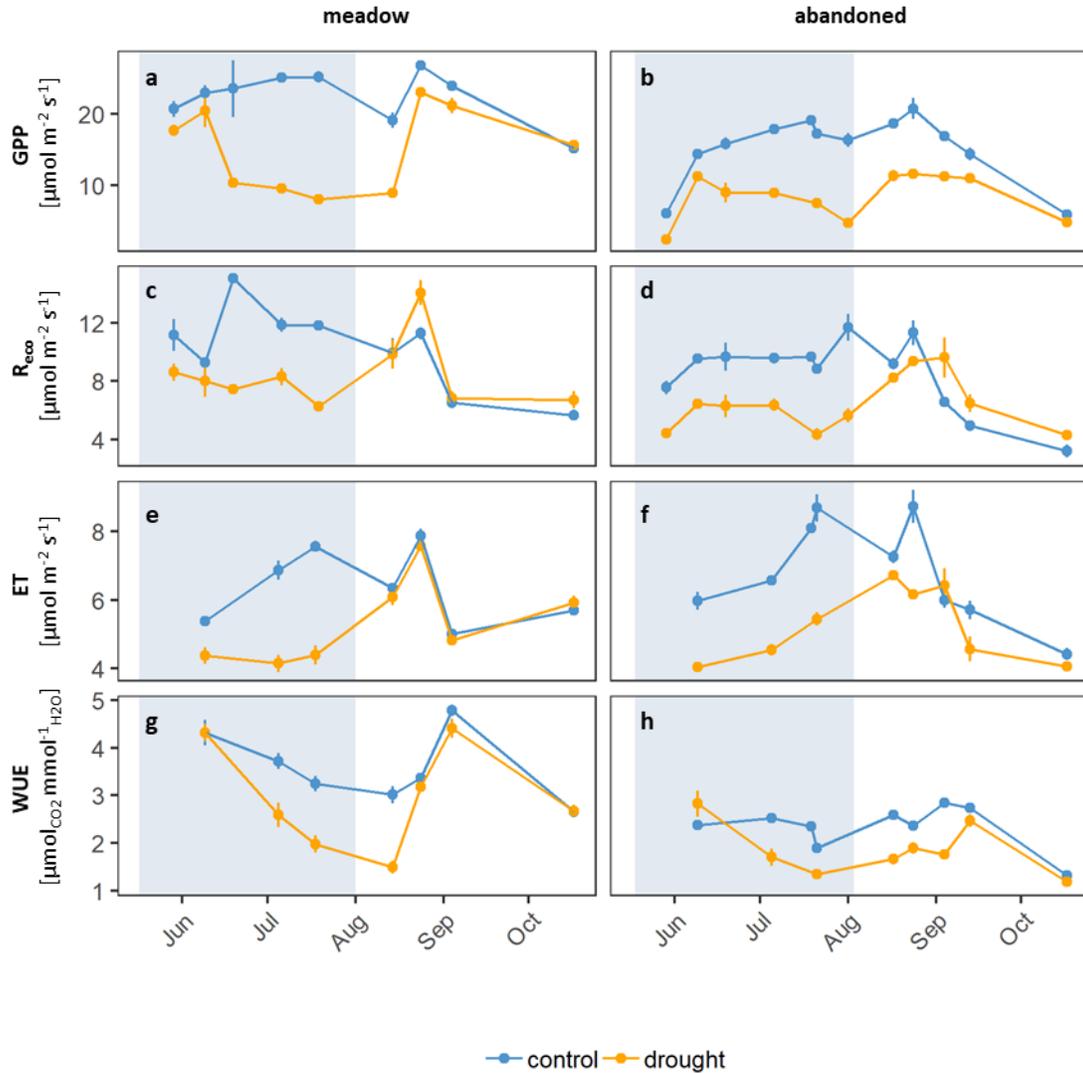


Figure 9: (a, b) Gross primary productivity (GPP), (b, c) ecosystem respiration (R_{eco}), (e, f) evapotranspiration (ET) and (g, h) water-use efficiency (WUE) of the meadow (left) and the abandoned (right) grassland over the course of the experimental season in 2017. Color denotes the drought treatment, error bars indicate $\pm SE$. Shaded area indicates the time of the rain-out sheltering.

3.4 Dendroecological analysis of Norway spruce and European larch on the hillslopes

Radial growth indices are known to be valuable short- and long-term measures of overall tree vigour (Dobbertin 2005). Drought-triggered declines in tree growth have considerably increased due to climate warming (e.g. Anderegg et al. 2015, Camarero et al. 2015), thus the main focus of dendroecological studies carried out within the project (Hölzl 2016, Höller 2017, Pircher-Nöckler 2017, Krismer 2018) has been to determine if heterogeneous topography and elevation act as a buffer against the influence of extreme drought events on tree growth in mountain forests dominated by Norway spruce (*Picea abies*) and European larch (*Larix decidua*). Both coniferous species are regarded to be drought sensitive (e.g. Levesque et al. 2013, Schuster and Oberhuber 2013, Zang et al. 2014), thus, we expected that in extremely dry years:

- i) selected tree species show different growth resistance and resilience (shallow-rooted Norway spruce more sensitive than deep-rooted European larch),
- ii) N-facing, mesic stands at high elevation show greater growth reduction and lower resilience than S-facing, dry-mesic stands at low elevation, and
- iii) higher tree density (i.e. competition) causes greater growth reductions and lower resilience.

Stands were selected in July 2016 along altitudinal transects on the S- and N-facing slope reaching from 1486–1798 m asl at transect ‘Kaserstattalm’, close to the experimental sites, and from 1122–1809 m a.s.l. at transect ‘Elferlifte’, on the other side of the valley, respectively. Cambic podzols are the dominant soil type. Forest stands selected along altitudinal transects differed in topography (convex vs. concave), water availability (dry-mesic vs. mesic) and density. In total 40 stands were selected and increment cores were taken from 10 trees per stand (400 cores in total). Core samples were extracted with an increment borer at 1.3 m stem height of each tree. Cores were taken parallel to the contour line to avoid stem areas with reaction wood, which generally occurs in stems of trees growing on steep slopes (Fritts 1976). In the laboratory, increment cores were air dried, glued in grooved wooden mounts and the surface prepared with a sharp razor-blade. Ring widths were measured to the nearest 0.001 mm under up to 60x magnification using an incremental measuring table. The correct dating of tree ring series was checked using Cofecha (Holmes 1994, Grissino-Mayer 2001), which identifies segments within each ring series that may have erroneous cross-dating or measurement errors.

Ring width was converted into basal area increment (BAI) to remove variation in radial growth attributable to increasing circumference according to the equation:

$$BAI = \pi (R_n^2 - R_{n-1}^2)$$

where R is the radius of the tree inside the bark and n is the year of tree ring formation. An estimate of bark thickness was used to estimate the radius inside the bark. Diameter at breast height was measured at the time of core sampling.

The comparison of forest growth before, during and after the drought event using resilience indices provides information on forest recovery after drought. We followed Lloret et al. (2011) to define resistance and resilience based on ratios of tree growth (BAI) during the drought period and growth during previous and subsequent years.

$$\text{Resistance} = \text{BAI}_D / \text{BAI}_{\text{preD}}$$

$$\text{Resilience} = \text{BAI}_{\text{postD}} / \text{BAI}_{\text{preD}}$$

where BAI_D is the BAI during the corresponding drought period, BAI_{preD} is the average BAI for the 5 years preceding the drought event and $\text{BAI}_{\text{postD}}$ is the average BAI for the 5 years following the drought event. Indices were calculated at the individual tree level. Competition between trees was quantified based on measurements of stem diameter and linear distance among trees competing with each other (Hegyí 1974).

The standardized precipitation index (SPI; Keyantash et al. 2002) and the De Martonne aridity index (De Martonne 1926) for the period from June to August was used to identify extreme dry years between 1947 and 2015 based on precipitation and temperature data of the HISTALP data set (Auer et al. 2007). For these extreme years, the resilience and resistance of BAI was calculated for European larch (n=161) and Norway spruce trees (n=168).

The six most extreme dry years were 1947, 1962, 1976, 1984, 2003 and 2006. Only weak responses of the selected tree species to these years were found, i.e. summer drought did not have a severe impact on tree growth in the selected stands. However, site topography modulated radial growth response of trees to drought. Across the six driest years

- i) growth resilience against drought was not significantly different among Norway spruce and European larch ($p = 0.139$; Fig. 10), however, Norway spruce shows higher resistance to drought compared to European larch ($p < 0.01$).
- ii) trees on south-facing slopes recovered faster from dry years than those on north-facing slopes (Fig. 11), and
- iii) growth resistance and resilience increased with elevation (Fig. 12).

Furthermore, Norway spruce stands located on moist sites had higher resistance and resilience to drought compared to dry-mesic sites (Fig. 13), while increasing competition (i.e. stand density) decreased growth resilience and resistance of both species (Fig. 14).

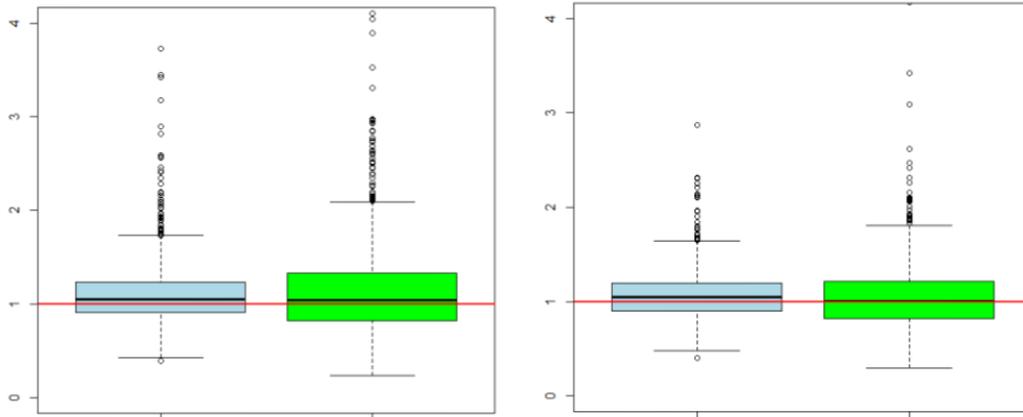


Figure 10: Boxplots of resilience (left) and resistance (right) of Norway spruce (blue) and European larch (green) as a function of all dry years (outliers > 4 not shown; Krismer 2018).

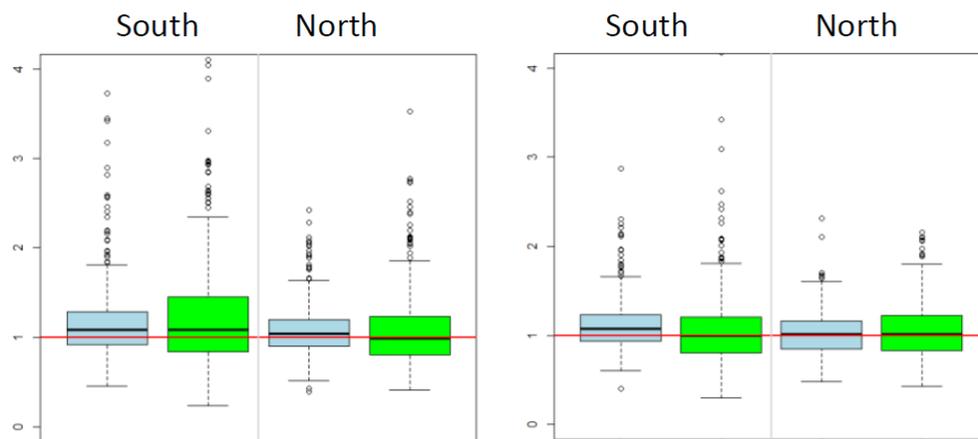


Figure 11: Boxplots of resilience (left) and resistance (right) of Norway spruce (blue) and European larch (green) as a function of slope aspect (Krismer 2018).

Growth resilience and resistance of south-facing stands to drought is significantly higher compared to north-facing stands ($p < 0,001$ and $p = 0.0205$, respectively; Fig. 11). Both species show significantly higher growth resilience and resistance to drought at subalpine sites compared to montane sites ($p < 0.001$; Fig. 12). While no significant difference in resilience and resistance to drought was found among selected site types for European larch ($p > 0.1$), Norway spruce showed higher resilience and resistance to drought on mesic sites compared to dry-mesic sites ($p < 0.01$; Fig. 13).

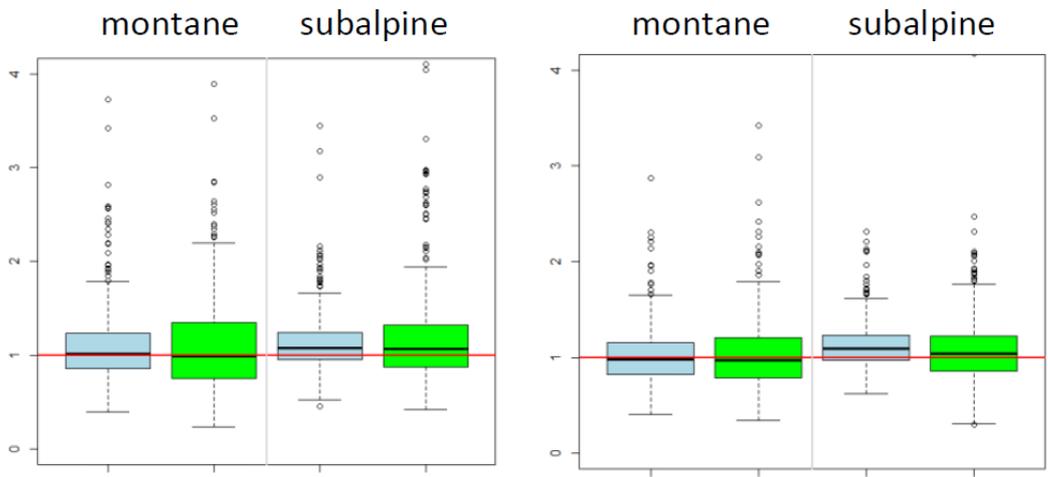


Figure 12: Boxplots of resilience (left) and resistance (right) of Norway spruce (blue) and European larch (green) as a function of elevation (Krismer 2018).

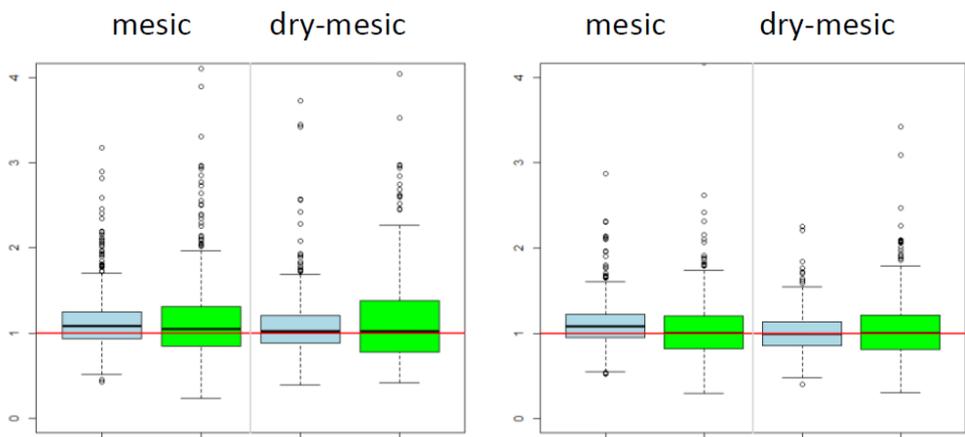


Figure 13: Boxplots of resilience (left) and resistance (right) of Norway spruce (blue) and European larch (green) as a function of water availability (Krismer 2018).

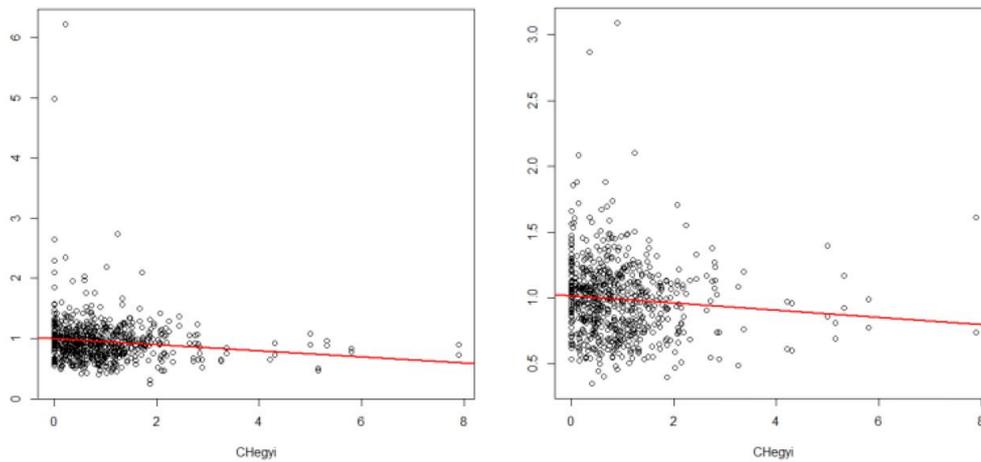


Figure 14: Linear relationship (Spearman-correlation) between resilience (left) and resistance (right) and competition index (Chegyi; Krismer 2018).

Resilience and resistance are inversely correlated to the competition index ($p < 0.001$) indicating that with increasing competition, growth resilience and resistance to drought are decreasing (Fig. 14). For individual species, resilience and resistance are significantly affected by competition in Norway spruce, while only resistance is significantly affected by competition in dry years in European larch.

Overall, the dendroecological findings suggest only minor growth responses of Norway spruce and European larch to extreme drought during the growing season, indicating that in the Stubai Valley current precipitation is sufficient to maintain adequate tree growth from the montane to the subalpine zone, irrespective of slope aspect and soil water availability (dry-mesic vs. mesic sites). Although Norway spruce showed higher growth resistance to drought compared to European larch (considering the six most extreme dry years), no statistically significant difference in the capacity to recover to pre-growth levels (i.e. resilience) after drought was found between the species. However, growth resilience and resistance to drought were significantly higher for both species on south-facing slopes, at higher elevation (subalpine) and on mesic sites. Furthermore, in dense stands competition caused significant reduction of growth resilience and resistance under drought. Hence, results revealed that under climate conditions prevailing in the previous decades in the Stubai valley, forest resilience to drought was mainly dependant on site conditions (i.e. aspect, elevation, soil water availability and stand density), and only secondarily on tree species. Hence, we could not confirm our hypotheses that Norway spruce and European larch show different resilience capacity and resistance to drought. Furthermore, growth resistance and resilience increased with elevation and soil water availability, disproving our hypotheses regarding site-specific effects with the exception of slope aspect. In this regard, our expectation that N-facing stands show lower growth resilience and resistance was confirmed. Results also confirmed our third hypothesis that higher tree density (i.e. competition) causes greater growth reductions and lower resilience to extreme summer drought.

Missing distinct growth response of selected stands to low summer precipitation can be explained by adequate soil water availability for tree growth at mid to high elevation in the Stubai valley, even in

extreme dry years. At the afforestation treeline (1950–1990 m asl), temperature limitation of radial stem growth of young European larch and Norway spruce (tree age c. 20 yr at 50-60 cm coring height) was found by Hölzl (2016). At this location current summer temperature and previous October temperature primarily control radial growth of European larch (Spearman's rho (ρ) correlation coefficient 0.733, $p < 0.05$) and Norway spruce (ρ : 0.929, $p < 0.01$), respectively. Hence, it is reasonable to assume that under current climate conditions, low temperature during the growing season rather than precipitation is limiting radial tree growth of selected stands – especially at high elevation. Hence, results of this dendroecological study are in line with the growth limitation hypothesis of alpine treeline developed by Körner (1998) and several dendroclimatological studies conducted at mid- to high elevation (e.g. Oberhuber 2004, Leal et al. 2008, Hartl-Meier 2014). Furthermore, because precipitation and temperature are inversely correlated (i.e. during drought periods higher temperatures prevail than during wet periods and vice versa), tree growth limitation by temperature also explains why at high elevation, on N-facing slopes, and on mesic sites, a higher resistance and resilience of radial stem growth to drought was found.

We conclude that in mountain forests of the Stubai valley (i.e. above 1100 m asl up to the treeline), Norway spruce and European larch remain suitable tree species even under moderately changing climatic conditions. Adaptive forestry measures, e.g. increasing percentage of deciduous woody species to improve soil conditions, considering more drought tolerant conifers such as silver fir (*Abies alba*) in future afforestations (Vitali et al. 2017), and reducing stand density to decrease competition might help to maintain forest stability and productivity under a warmer climate particularly on drought-prone sites, i.e. on S-facing slopes with convex topography at low elevation (Bolte et al. 2009, Kohler et al. 2010, Gebhardt et al. 2014).

3.5 Drought effects on subalpine forest

While the dendro-ecological analysis indicates possible effects of past climatic events on tree growth, it provides limited insight into the effects of possible future extreme droughts, which are expected to increase in frequency and severity in the coming decades. To experimentally test for such possible effects of severe recurrent drought events on growth and water use of the dominant tree species at the alpine tree line, we established a new long-term monitoring site with a nested replicated multiyear rain exclusion experiment. We hypothesized that (i) severe summer drought reduces tree growth and that (ii) water use will be significantly reduced due to a soil moisture deficit during drought periods. We expected (iii) saplings to be more vulnerable to drought than mature trees and that (iv) growth and water use responses to drought differ between the evergreen tree species Norway spruce and the deciduous tree species European larch.

As a major infrastructure achievement of the ClimLUC project, contributing to the LTSEr-Master site Stubai, a new study site was established in 2015. The subalpine forest is located at 1970 -2000 m a.s.l. between the managed the abandoned LTER grassland sites and is dominated by spruce and larch trees, most of which were planted in the 1980s on an abandoned pasture. Tree ring analyses of 46 spruce trees and 51 larch trees in 2015 revealed two distinct age classes in the local population of both tree species (Fig. 15), estimated at 15 ± 3.3 and 20 ± 3.7 years for spruce, and 18 ± 2.5 and 21 ± 3.6 years for larch, respectively (mean values and standard deviation, ages at coring height of 50 cm above ground).

At the mature forest stand, three drought plots with a size of approx. 200 m² and three control plots were established, each including two mature spruce (*Picea abies*) and larch (*Larix decidua*) trees (6–8 m high, 3.5–5.5 m crown diameter, 14–21 cm stem diameter at 1.3 m above ground). All of these trees (n=24) were equipped with circumference dendrometers (DC2 with data loggers DL15, Ecomatik, Germany) and sap flow sensors (EMS51A, Environmental Measuring System, Czech Republic). During the pre-treatment year 2015 radial stem growth of trees was measured continuously beginning in July. In addition, the sap flow sensors were tested after installation was accomplished in November 2015.

To test for effects of tree size on drought responses of radial growth and sapflow we established an additional rainout experiment on 24 saplings of Norway spruce and European larch (height: 4.9 ± 1.5 m, stem diameter: 7.9 ± 1.5 cm; mean \pm SD) in 12 paired plots, half of which were covered with transparent plastic sheets approx. 30 cm above ground to exclude precipitation on a minimum area of 16 m². All trees were equipped with sap flow sensors (M1 Sapflow System, PROSA-LOG; UP GmbH, Cottbus, Germany).

The drought treatment covered the main growing season from end of May until end of September in 2016, 2017 and 2018 (Table 1). In 2016 the treatment started two weeks later due to an exceptionally late and pronounced snowfall, reducing site accessibility and delaying the final preparation for the installation of large rainout roofs, thus the rainout treatment was less severe compared to the following years.

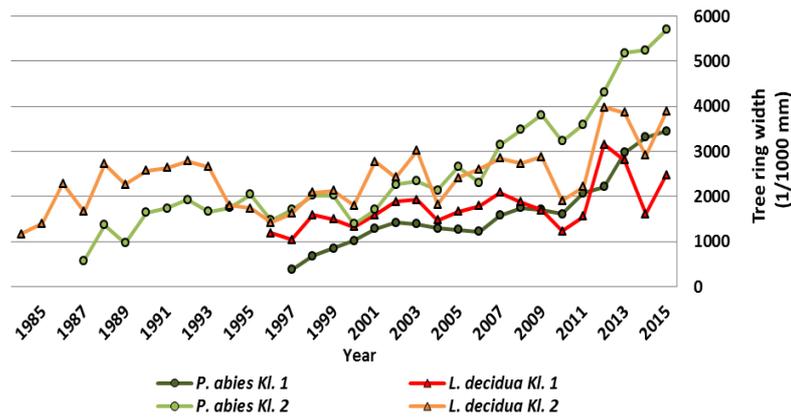


Figure 15: Tree ring width chronologies of two age classes of *Picea abies* (Kl. 1: 15 years, $n=23$; Kl. 2: 20 years, $n=23$) and *Larix decidua* (Kl. 1: 18 years, $n=21$; Kl. 2: 21 years, $n=30$) at the forest site.

Due to the late start of the treatment, growth dynamics were highest in the period before the drought in 2016. Also, significantly decreasing sap flux of drought-exposed could not be observed in 2016. With the drought treatment starting earlier in the growing season in 2017 and 2018, drought effects on radial growth were more pronounced, and were larger for spruce than for larch (Fig. 16). Sap flow rates and their threshold responses to environmental drivers were less affected by drought than radial growth, but tended to decrease under drought during periods of high evaporative demand, effects being more pronounced for spruce than for larch (Fig. 17). A preliminary analysis indicated that water use efficiency, expressed as radial growth per unit water lost during the growing season, decreased under drought for both spruce and larch, the effects being more pronounced for spruce (Fig. 18). Contrary to our expectation, saplings did not show any stronger drought responses of sap flow than adult trees. In 2018, at the end of the drought treatment stem conductivity was measured on spruce using in situ tomography, demonstrating that drought had significantly reduced conductivity across all sections of the trunk. This indicates the potential for an increased vulnerability of spruce to dry periods extending into the late season.

Overall, our findings indicate that, at the treeline, prolonged and recurrent drought periods can significantly reduce tree growth, affecting spruce more strongly than larch. However, while reducing hydraulic conductivity, extended drought periods were found to have only minor effects on water use at the alpine tree line.

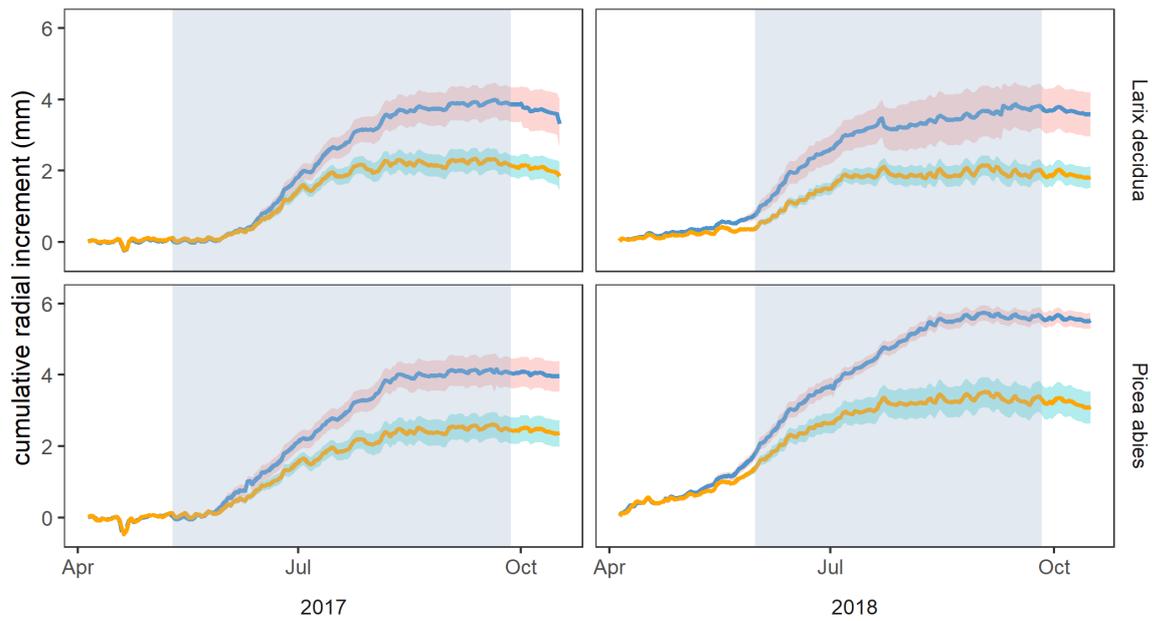


Figure 16: Cumulative daily radial increment (mm) of mature larch (*Larix decidua*) and spruce (*Picea abies*) in 2017 and 2018. Lines represent mean of control (blue) and drought-exposed (orange) trees ($n = 6$ per species and treatment); Shadings indicate SE.

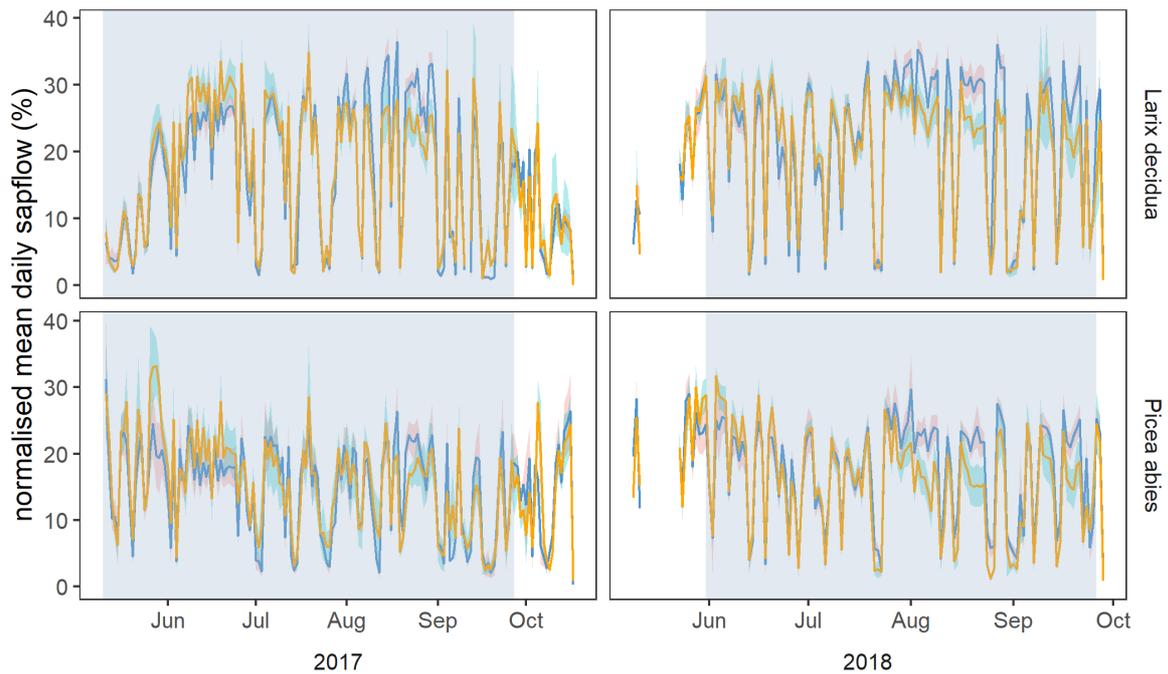


Figure 17: Daily mean sap flow of mature European larch (*Larix decidua*) and Norway spruce (*Picea abies*) in control (blue line) and drought-exposed (orange line) plots in 2016, 2017 and 2018. Values given are mean daily sap flow rates \pm SE, normalised to maximum sap flow capacity of each individual tree ($n = 6$ per species and treatment). Shaded area indicates the period of rain exclusion.

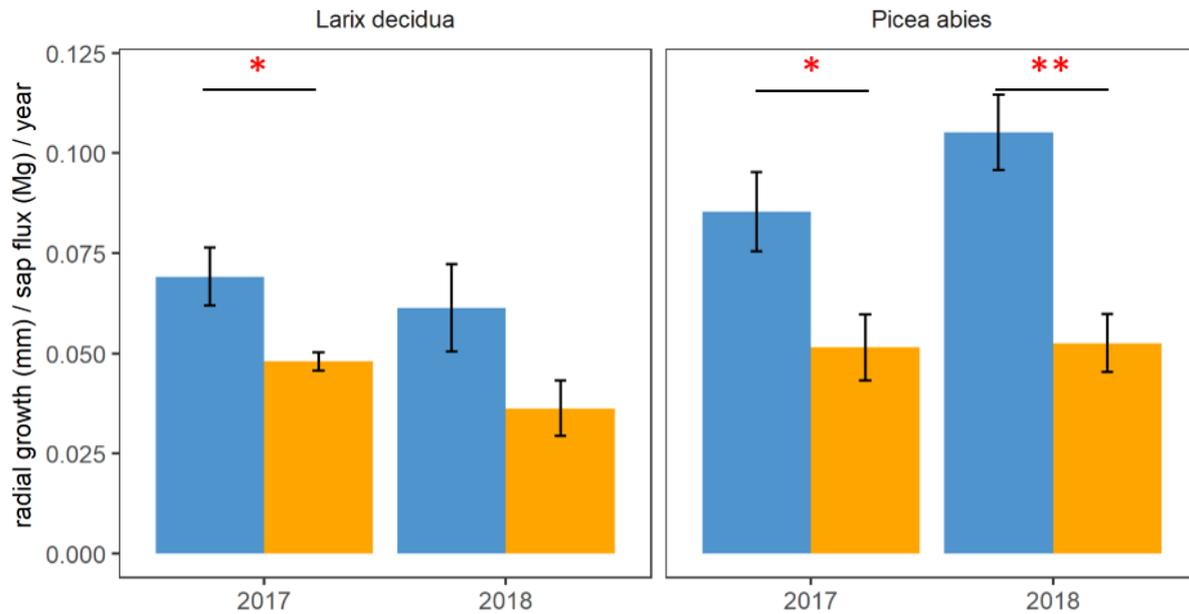


Figure 18: Seasonal water use efficiency, approximated as cumulative seasonal radial growth (mm) per cumulative seasonal water loss (Mg) for mature Larch (*Larix decidua*) and spruce (*Picea abies*) under ambient (blue) and rain-exclusion conditions (orange bars) in 2017 and 2018. Error bars indicate SE; * = p -value < 0.5; ** = p -value < 0.05; n = 6 per species and treatment.

3.6 Summary and conclusions

Work package 1 performed a detailed investigation into the effects of land use changes and drought on plant and ecosystem processes in mountain grasslands and forest, utilising both natural variability in microclimate and manipulative experiments. The first set of studies involved comparison of trace gas fluxes and drought responses between an abandoned grassland and a managed meadow. The results clearly showed that abandonment of mountain grasslands leads to decreased productivity and reduced greenhouse gas fluxes, and alters nitrifier and denitrifier abundances and plant stoichiometry. Drought resilience is affected by plant strategies dominating different land-use types and by plant-microbe interactions. To assess resilience, both resistance and recovery need to be jointly considered. Our observations showed that abandonment reduces overall perturbation by drought and thereby increases resilience to drought; however, the abandoned grassland showed slower recovery from drought. Legacy effects of repeated drought on grassland productivity were also considered: Recurrent drought was found to increase susceptibility of productivity, CO₂ fluxes and water use efficiency to subsequent drought.

The effects of water limitation on tree growth were considered using both altitudinal transects with varying topography and water availability and manipulative water exclusion experiments. The transect results showed that under current conditions, radial growth of spruce and larch was barely influenced by water limitation. However, drought resilience and resistance were significantly affected by competition (higher tree density) for Norway spruce in all years and for European larch in dry years. In comparison, the manipulative experiments showed that possible future severe drought events can significantly affect radial growth, and to a lesser degree, sap flow. Spruce is more

susceptible to drought than larch, exhibiting stronger reductions in both radial growth and water use efficiency. When comparing results across both grassland and forest experiments, we found that – contrary to our expectations – drought consistently decreased water use efficiency.

In conclusion, our findings suggest that land-use changes and related effects on plant and microbial composition and functioning can significantly alter the responses of mountain ecosystems to severe drought. While resilience to drought generally decreased from managed to abandoned grassland and forest, legacy effects may alter drought response trajectories, with so far poorly understood consequences for the provisioning of ecosystem services in a changing world.

4. Ecosystem modelling (Work Package 2)

Nicolas Viovy

4.1 Response of ORCHIDEE model to change in precipitation

Our first objective was to understand how the ORCHIDEE model responds to changes in precipitation. For this purpose, we used climate forcing data already available at the Stubai site at the beginning of the project. We modified the in situ precipitation forcing by removing a fixed fraction of precipitation at each timestep. We then considered four precipitation levels, ranging from 20% to 50% of the measured precipitation. Figure 19 shows the simulated gross primary production in response to the four levels of precipitation reduction. In collaboration with a related project, INTERFACE, this experiment was also conducted for an ensemble of 14 different terrestrial models. Figure 20 shows the response of GPP, NPP and carbon use efficiency (CUE) to different levels of total precipitation at Stubai simulated by an ensemble of 14 models. With this simulation ensemble, it is possible to see how ORCHIDEE compares to similar terrestrial models, and to estimate the contribution of terrestrial model choice to uncertainty (Wu et al 2017).

In Figure 19 we can see that for Stubai – a relatively wet site – shows a significant response only when precipitation is decreased by 70%. When precipitation is reduced to <30% of normal levels, the decrease in GPP is very sharp. This is also clearly visible in Figure 20 (Wu et al. 2017). While there is a large range of simulated GPP or NPP between the 14 models, the shape of the response to decreased precipitation is very similar (except for two models) and the amplitude of decrease is related to the mean level of NPP and GPP in each model. The modelled response from ORCHIDEE is very close to the median of all the models.

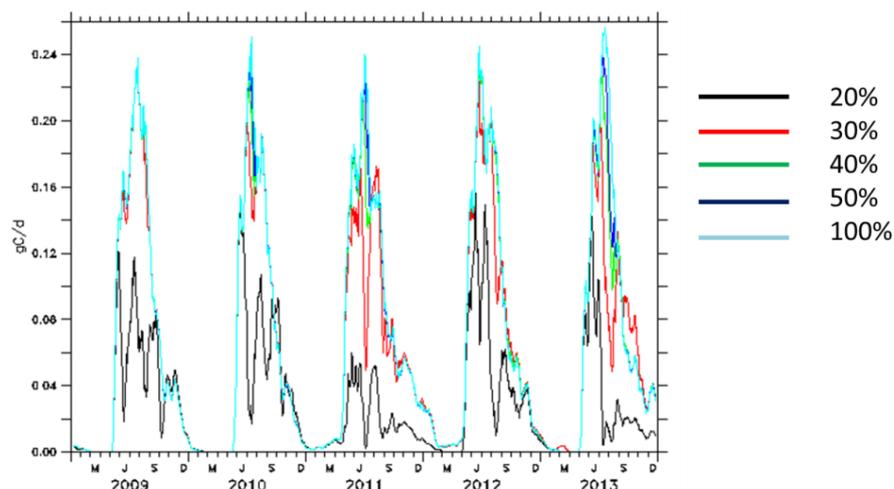


Figure 19: Simulated carbon uptake for different level of precipitation using the ORCHIDEE model (100% represents the actual precipitation at the site).

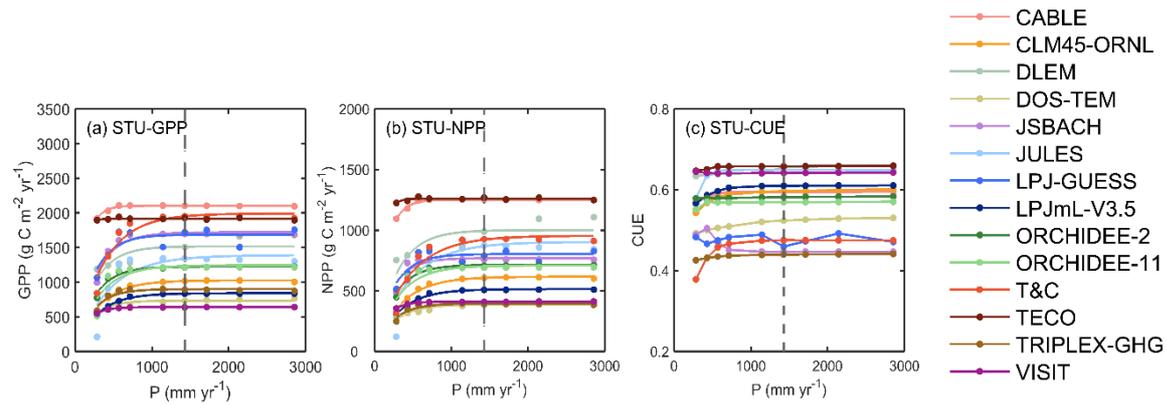


Figure 20: Asymmetric response of GPP, NPP and carbon use efficiency for an ensemble of models for the Stubai site. The mean measured precipitation at the site is indicated by the vertical dashed line.

4.2 Comparison of simulated response in ORCHIDEE with in situ data from rain exclusion experiments

Using data provided from WP1 after the 2017 campaign, a set of simulations on for the three land-use types (sub-sites) at the Stubai site (meadow, abandoned and forest) was conducted for control and rain-out experiments. To run this simulation, the model was forced using in situ measurement of meteorological data. Pre-processing of meteorological data was necessary to gap fill for missing data to produce a complete yearly time series. The simulation was then compared to in-situ measurements of GPP, NEE, TER, LAI and biomass.

ORCHIDEE was first run for the 3 sub-sites using input meteorological data for 2017 until an equilibrium for the vegetation and soil carbon pools was reached. Starting from this steady state, the control and rain exclusion scenarios were tested. Figure 21 shows the evolution of GPP in the simulation compared to observations for the meadow and abandoned sites for the two different scenarios, control and rain exclusion. GPP for the abandoned site is well simulated for both control and rain exclusion cases. For the meadow site, the GPP is underestimated (probably related to the fact that we use same parameters for meadow and abandoned sites whereas meadow is more productive). But here again, the direction of the difference between the simulations with and without rain is correct. However, we tend to underestimate the regrowth after the rain exclusion ends. This is probably related to the fact that this version of ORCHIDEE does not represent the nitrogen cycle, and therefore lacks a pulse in soil nitrogen remobilisation following rewetting that may enhance photosynthesis. The latest version of ORCHIDEE explicitly includes the nitrogen cycle, thus it will be interesting in the future to test if simulation of the full coupled C/N cycle improves the simulated response to drought.

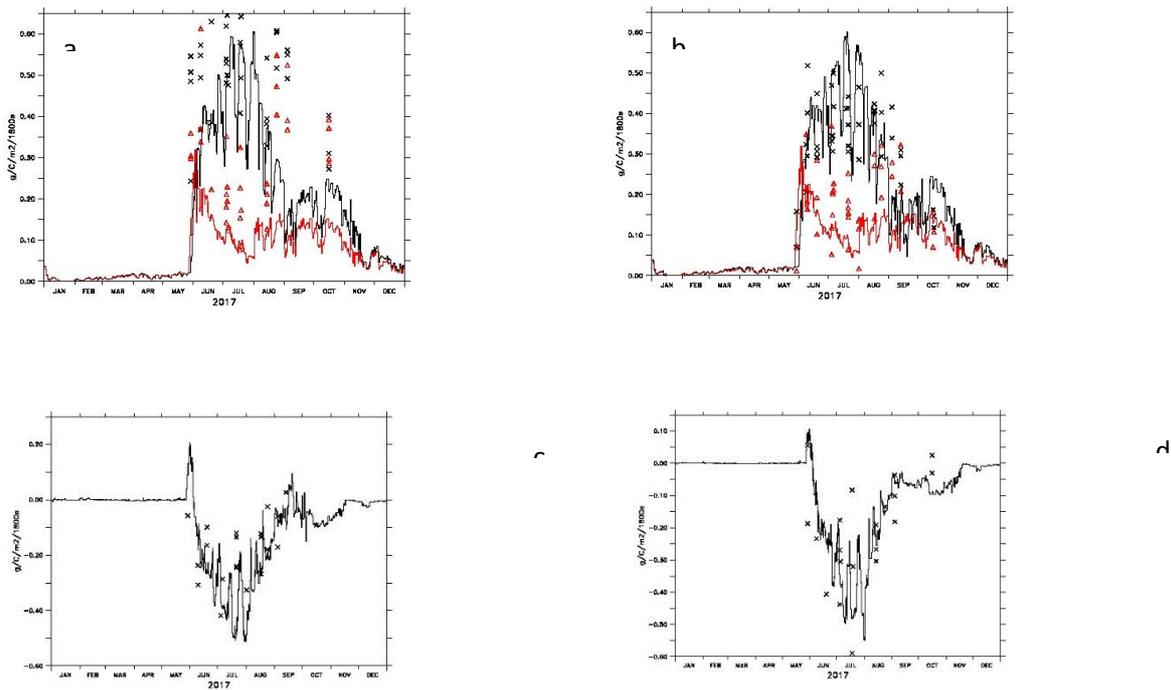


Figure 21: Simulated and observed GPP for meadow and abandoned sites. Solid lines are simulations from the ORCHIDEE model and the symbols are observations. A, C: meadow, B, D: abandoned. A, B: absolute values, black is control, red is rain exclusion: C, D: differences between rain exclusion and control sites.

The simulated and observed results for NEE for the meadow, abandoned and forest subsites are shown in Figure 22. Contrary to GPP, the best agreement is observed for the meadow, but the difference between control and rain exclusion is similar. The simulated and observed total ecosystem respiration (TER) for the abandoned site is shown in Figure 23. Unlike GPP and NEE, the results show a large discrepancy between observed and simulated TER. This is relatively surprising since we could expect that a correct simulation of GPP and NEE should also leads to correct TER, as $NEE = GPP - TER$. This may be related to the fact that respiration processes in ORCHIDEE are not fully represented at hourly time step, and thus strongly underestimate diurnal course of respiration, even if it is correct at the daily time step. This comparison may help to refine respiration processes in ORCHIDEE.

The simulated and observed LAI as well as the difference between control and rain exclusion scenarios is shown in Figure 24. We tend to slightly underestimate LAI for the control but we clearly overestimate LAI reduction with rain exclusion. It seems then that allocation to leaves is less reduced than GPP. One hypothesis could be that reduction of soil water largely reduce allocation to fine roots that is then transferred to leaves.

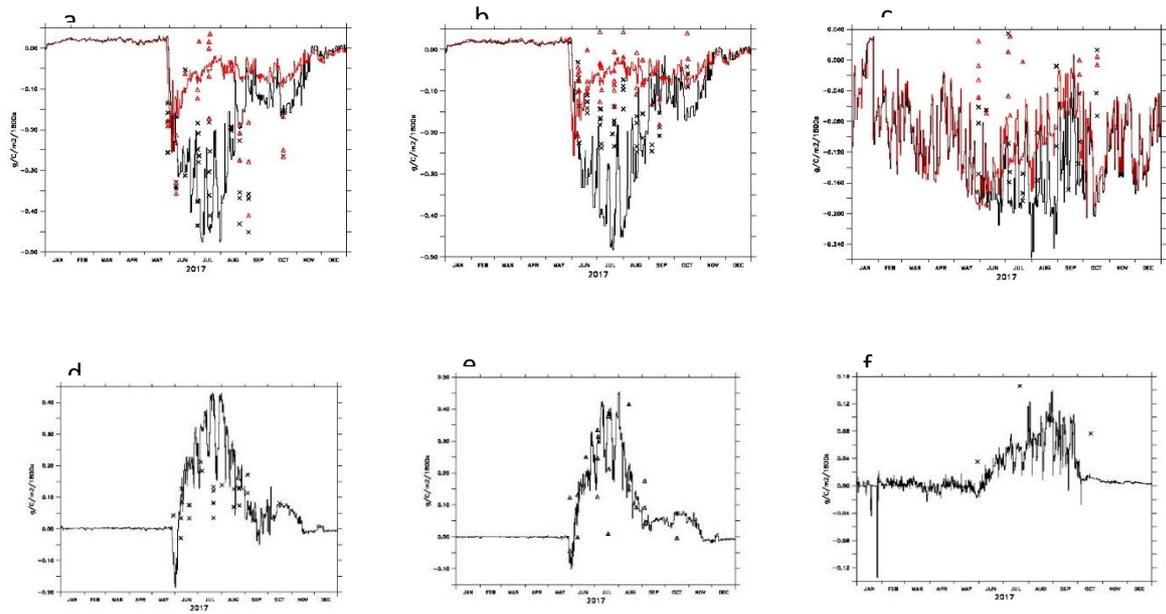


Figure 22: Simulated and observed GPP for meadow and abandoned sites. Solid lines are simulations from the ORCHIDEE model and the symbols are observations. A, C: meadow, B, D: abandoned. A, B: absolute values, black is control, red is rain exclusion: C, D: differences between rain exclusion and control sites.

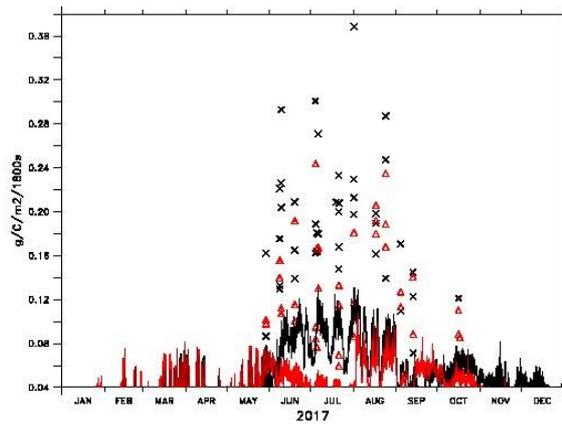


Figure 23: Simulated and observed TER at abandoned site. Solid lines are simulations, symbols are observations. Black is control, red is rain exclusion.

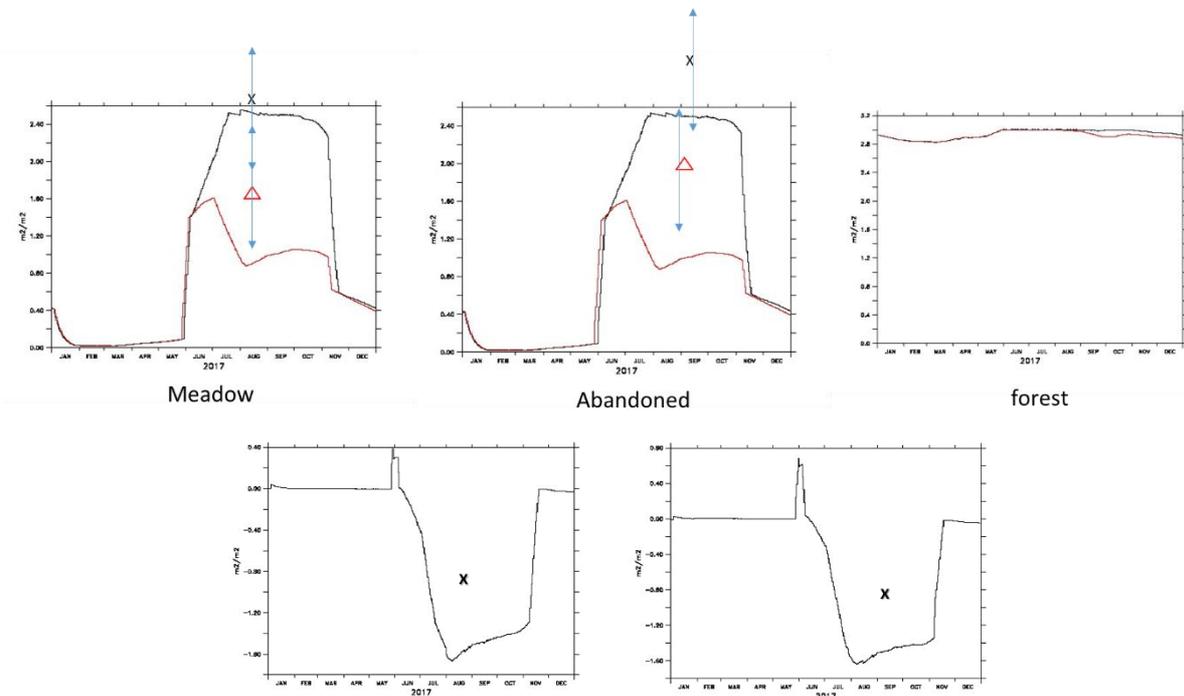


Figure 24: Simulated and observed LAI for the three sites (no LAI observations are available for the forest site). Solid lines are simulations; symbols are observations (with inter-site variability). Black is control, red is observations.

4.3 Simulations at the level of the full STUBAI valley

To estimate the spatial variability of the vegetation response to extreme events at the level of the whole Stubai valley, we conducted a set of 2D simulations with a spatial resolution of 1 km. We first prepared a forcing dataset based on a combination of the harmonized WATCH-ERA reanalysis dataset covering Europe for the period 1957 to 2010 at a spatial resolution of $0.25^\circ \times 0.25^\circ$ at a daily time step, and the WORLDCLIM global 1 km monthly climatology (<http://www.worldclim.org/>) to produce a pseudo-1 km dataset for the entire STUBAI valley with a domain of 397 pixels. A similar dataset was produced for the future climate scenario (2010-2100, A1B baseline). A land use map was provided by WP3 for the historical period at 1 km spatial resolution.

Different simulations were then performed:

- (1) A standard simulation for the period 2000-2010. Model was first run for spin up until equilibrium was reached and then run for the period 2000-2010.
- (2) A simulation beginning from the equilibrium state of simulation 1 and run for 10 years with all precipitation removed from May to August, to mimic the rain exclusion experiment.
- (3) Same simulation as (2) but with rain exclusion used for spin-up to study the legacy effects.
- (4) A future simulation with the future climate scenario beginning with equilibrium state of (1)
- (5) A series of simulations with precipitation reduced by 20%, 30%, 50% and 70% of original precipitation (constant decrease applied each day) for period 2000-2010

For all simulations, atmospheric CO₂ is held constant at the current mixing ratio.

The impact of rain exclusion on simulated NPP for both grassland and forest is shown in Figure 25. In B and D, we considered, like in the in-situ experiment, a rain exclusion starting from vegetation growing in normal conditions. For C and F we consider a simulation where vegetation was growing in the condition of rain exclusion from the beginning of the simulation to mimic a vegetation that was growing in degraded rainfall condition for long time to see the legacy effect of exclusion. We can see for both grassland and forest a strong reduction in NPP, that can reach more than 80% of the total annual productivity. The reduction is stronger for grasslands, which have shallow roots compared to forests, and thus are not able to access winter soil water recharge in deeper layers. Forest areas show a relatively homogeneous response for the whole the domain, while grasslands show large contrasts in response between low and high altitude, whereby grasslands located at higher altitude show only slightly reduced productivity. This changes the direction of the productivity gradient in the valley: In the control simulation highest grassland productivity is in the valley floor while in the drought simulation highest productivity is at higher altitude. This could be related to several different factors. Firstly, precipitation is higher on the mountain side making the reduction less important. Furthermore, later snow melt recharges soil water at high altitude at the beginning of the exclusion period. Finally, the soil water depletion is less rapid at high altitude because of lower evaporative demand, related to lower temperature and LAI.

To evaluate the response curve considering different levels of precipitation reduction, we conducted a series of simulations with a constant fraction of precipitation removed every day. The change in NPP considering different theoretical rainfall reduction levels is shown in Figure 26. A value of 1 (blue) represents no change in NPP whereas a low value (brown) represent a high NPP reduction (up to 60%). For the highest reduction level (80%), the response is similar for grassland and forest. However, at intermediate levels the NPP reduction for grassland is linearly related to precipitation change, whereas the forest exhibits almost no change until 50% of precipitation is removed, following which a sharp decrease in NPP is observed. We can also notice that, for grassland, we have opposite behaviour compared to the summer drought; when precipitation reduction is even throughout the year, NPP reduction is strongest at higher altitude. When precipitation reduction is distributed through the year, there is still some precipitation in summer, thus soil water at low altitudes is not totally depleted. This demonstrates that the distribution of precipitation reduction is crucial.

To evaluate the response of productivity based on a real climate change projection, we performed a simulation based on the downscaled A1B scenario (Figure 27). In contrast to the reduced precipitation simulations, here we simulate an increase of NPP compare to current NPP. This can be explained by the fact that precipitation is only slightly reduced in this scenario. Temperature is an important limiting factor in this region, thus the increased temperature in the future climate scenario leads to increased vegetation productivity, which outweighs the negative effect of reduced precipitation. These conclusions should be considered with caution. Firstly, the climate scenario

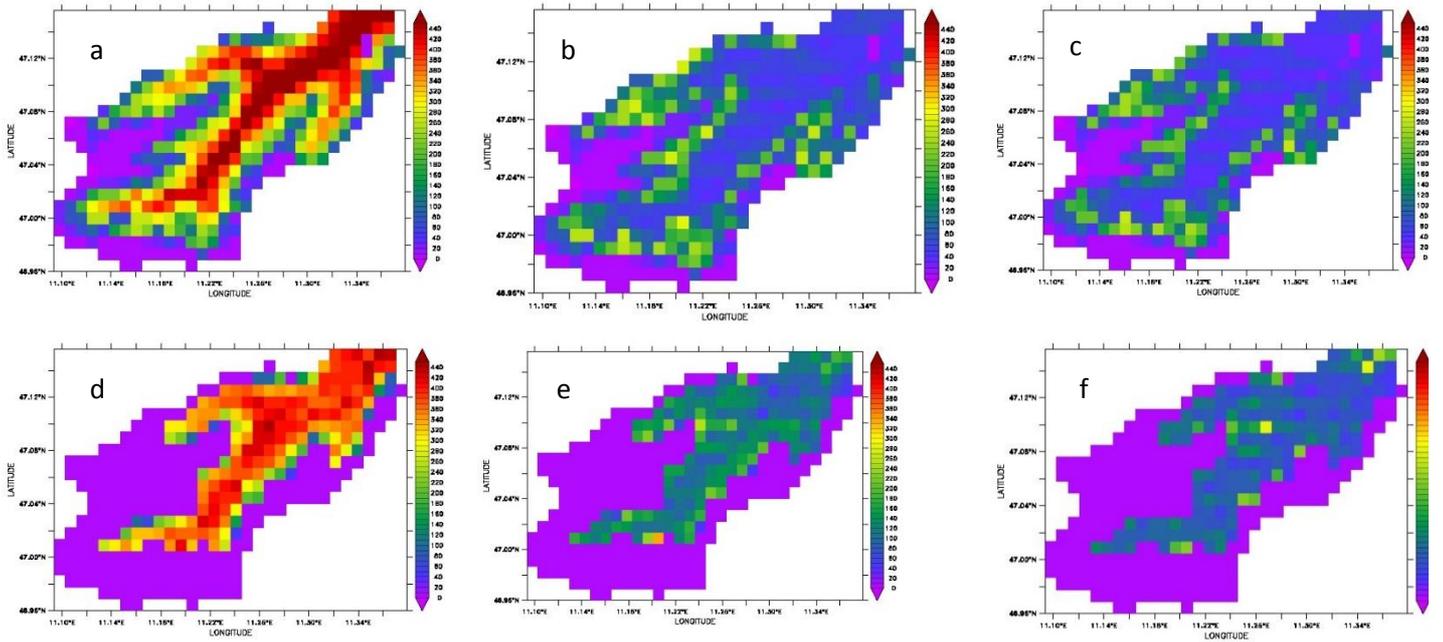


Figure 25: Simulated mean annual NPP (a, d): with normal precipitation (b, e): with reduced precipitation but starting with equilibrium state of normal precipitation. (c, f): with reduced precipitation applied for all the simulation. (a,b,c): grassland. (d,e,f): forest

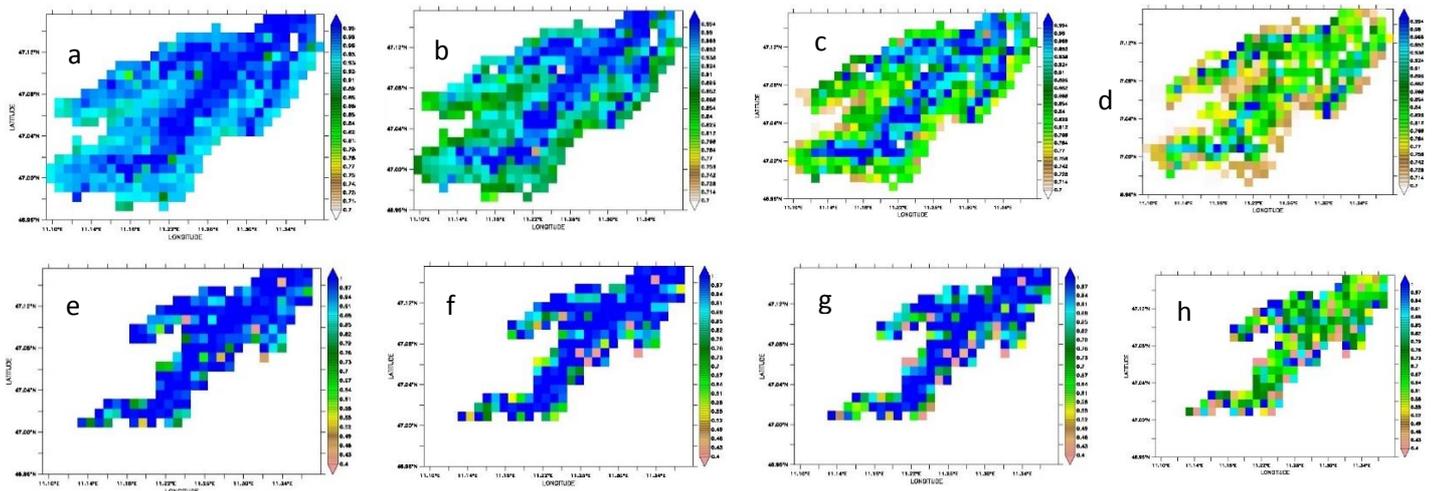


Figure 26: Simulated NPP reduction (compared to normal NPP) with different levels of rainfall reduction. (a,e) 30% of reduction (b,f): 50% of precipitation, (c,g): 70% of reduction. (d,h): 80% of reduction. (a,b,c,d): grassland. (e,f,g,h): forest.

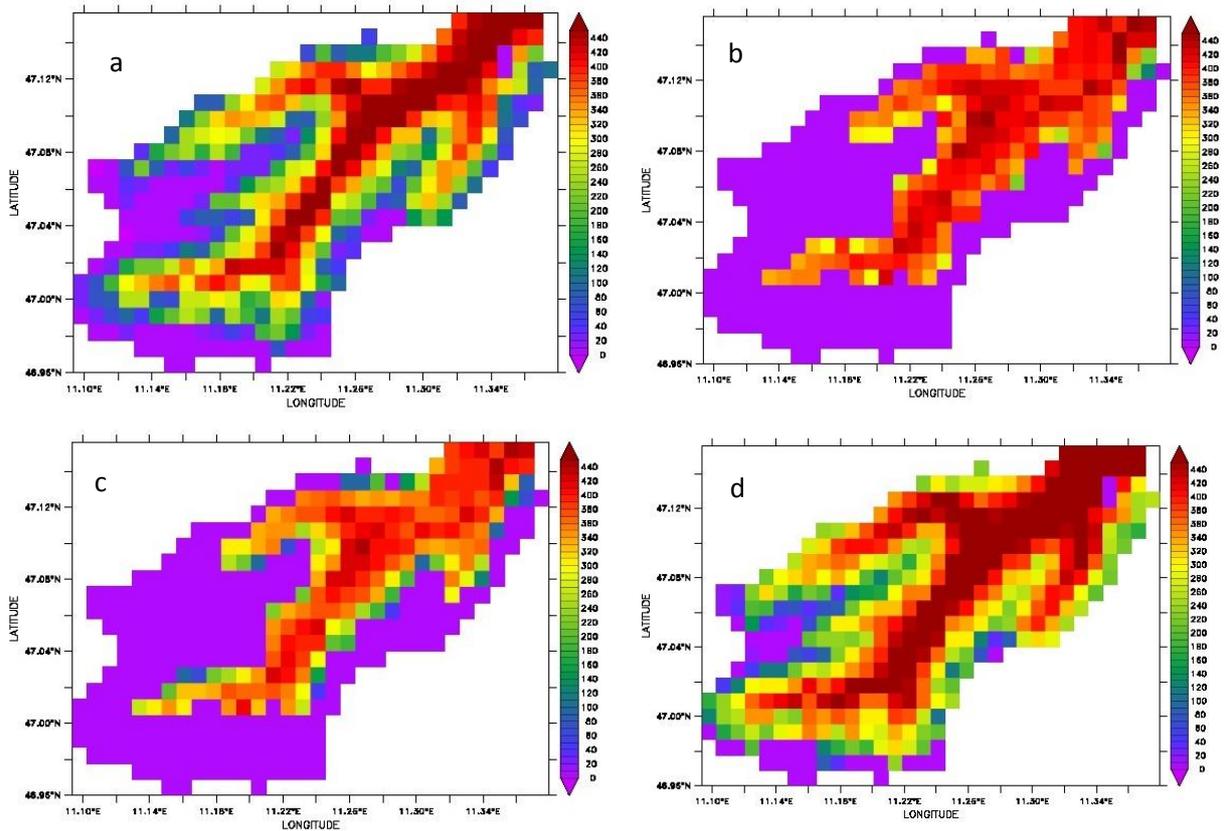


Figure 27: Simulated mean annual NPP (a,c): for 2000-2010 period (b,d): for 2090-2100 period, A1B scenario.

considered (A1B) is based on a relatively limited level of climate change. The downscaled scenario is based on a global climate model that is not able to reproduce correctly the spatial and temporal high resolution change of precipitation especially in mountain regions. In particular, such models tend to underestimate extreme events like large drought.

4.4 Conclusion and perspectives

The project improved our understanding of how the ORCHIDEE model responds to extreme drought events, and how well it compares with in situ experimental results. The first step of the project was to evaluate the theoretical response of ORCHIDEE to precipitation reduction using in situ meteorological data. The simulations showed a nonlinear response of modelled GPP/NPP etc. until precipitation was reduced by X%, following which productivity sharply decreased. It was also possible to compare the response of ORCHIDEE with others land surface models, which show a range of absolute values but a similar non-linear response curve (Wu et al. 2018). Extending these simulations to the whole Stubai valley allows us to evaluate the heterogeneity of the response, and differences between forest and grassland. The non-linear response observed for the site scale simulation is coherent with what we observe for forest, whereas grassland seems to respond more gradually, with GPP significantly affected with a lower precipitation decrease. This may be because grassland, which

only has roots in the top of the soil, is more sensitive to soil water reduction. The response of grassland is also more heterogeneous than forest, with a different response between grassland in the valley floor and at higher altitude.

Using data acquired in WP1, it was possible to compare the model response to the response observed in the field for the three land use types. In this case, rain exclusion is only during spring and summer and not distributed throughout the year. This comparison between model and experiment demonstrate that the model is able to reproduce the impact of rain exclusion of simulated carbon fluxes. Some differences are however visible that may help to improve model parameterization. In particular, it was interesting to see that the model could not reproduce the grassland regrowth after end of the rain exclusion period. This could be related to interactions between water and the nitrogen cycle that are not accounted for in the current version of ORCHIDEE. It will be interesting to see if the discrepancy is reduced with the new version of ORCHIDEE, which will include a full coupled nitrogen cycle. In some cases, the model also slightly overestimates the effect of drought, which could be related to the strength of the vegetation response to hydric stress or a poor representation of the root profile. A similar simulation was also performed for the whole valley. As for the simulations with distributed rainfall decrease, the response was homogeneous for the forest but very heterogeneous for grassland. The spatial distribution of productivity reduction is opposite to what was simulated with distributed rainfall decrease: Grassland on the mountain side are only slightly affected by water reduction, whereas the effect is dramatic for valley grassland. This demonstrates that not only the mean annual change in precipitation but also the distribution of precipitation reduction is important. Hence, extreme drought events can have a dramatic effect even if the yearly precipitation is not strongly reduced.

We also performed a simulation based on a future climate scenario for the whole Stubai valley considering an A1B climate scenario for 2090-2100. The response of vegetation in this scenario is very different, since simulated productivity increases due to rising temperature. This demonstrates the large gap between experiment design and climate scenarios. One of the major limitations of the simulation is the low resolution of global climate models, which tend to underestimate the severity of extreme events – particularly for mountain regions with very heterogeneous climate conditions. Recent progress in development of regional models may improve these future predictions. The simulation results also show that experimental design should be carefully considered in the future, to develop field experiments that account for changes in multiple climate parameters. Model simulations show that effect of temperature increase in regions where temperature is an important limiting factor can alleviate the negative impact of drought events.

5. Ecosystem services (Work package 3)

Karl-Heinz Erb, Ulrike Tappeiner, Erich Tasser, Rupert Seidl

5.1 Provision and demand of ecosystem services in relation to climate and land-use changes

WP3 pursued two methodologically distinct sub-workpackages. The first sub-workpackage was completed in the second year of the project and followed a historical-empirical research strand. It aimed at quantifying the provision and demand of ecosystem services in the Stubai-valley from the mid-19th century until the present, in order to identify land use and management (changes), and to align these changes to the occurrence and regime of extreme events such as summer droughts. Starting point for the finalization of the first deliverable in WP3 (a research paper, see below) was a joint WP3 meeting in the end of February 2016 at the University of Innsbruck, in which remaining methodological issues, preliminary results, the time-schedule for the writing process, as well as the next steps were discussed. The empirical work was finalized by summer 2016, allowing for a submission of the paper to “Ecosystems” and for an oral presentation of the results at an international conference (see below).

The main findings of the study were, that land management, assessed by applying the indicator framework ‘Human Appropriation of Net Primary Production’ (HANPP), was a central determinant for the massive C-stock increases in the Stubai-valley from 1865 to 2003. Two different phases of land-use could be distinguished: Until the 1950s, intensive use of forest land and a high importance of agriculture to the local economy dominated the land-use system and resulted in rather low C-stock levels combined with high HANPP, signalling high land-use impacts. Until the 1950s, around 30% of the annual forest NPP was consumed by the livestock sector in the form of forest grazing and litter extraction, pointing to a very close integration of the forest and the livestock system in pre-industrial times. In the consecutive period, land-use shifted to completely new courses. Polarization into high-intensity low-land areas and extensification at higher altitudes allowed for a tripling of standing carbon of current (actual) vegetation (SC_{act}) until 2003 (Fig. 28). The most important land-use change was the intensification of the livestock sector accompanied by abandonment of extensive grasslands and a reduced harvest pressure on forests after WWII. Market integration, abundance of fossil energy carriers, as well as structural change of the economy were important underlying socio-economic drivers of these trends (Niedertscheider et al. 2017).

However, despite this remarkable SC_{act} increase, SC_{act} amounted to only 62% of the potential carbon stocks (SC_{pot}) in 2003 (Fig. 28). While conversion of forests to agriculture clearly contributed a large share to this C-gap, forest management explains roughly one quarter of the SC-difference. Time-lags between land-use shifts and the establishment of a new C-climax had fundamental repercussions on recent C-dynamics in the study region. Apparently the land system is still net-accumulating C, although land-use changes have peaked decades earlier.

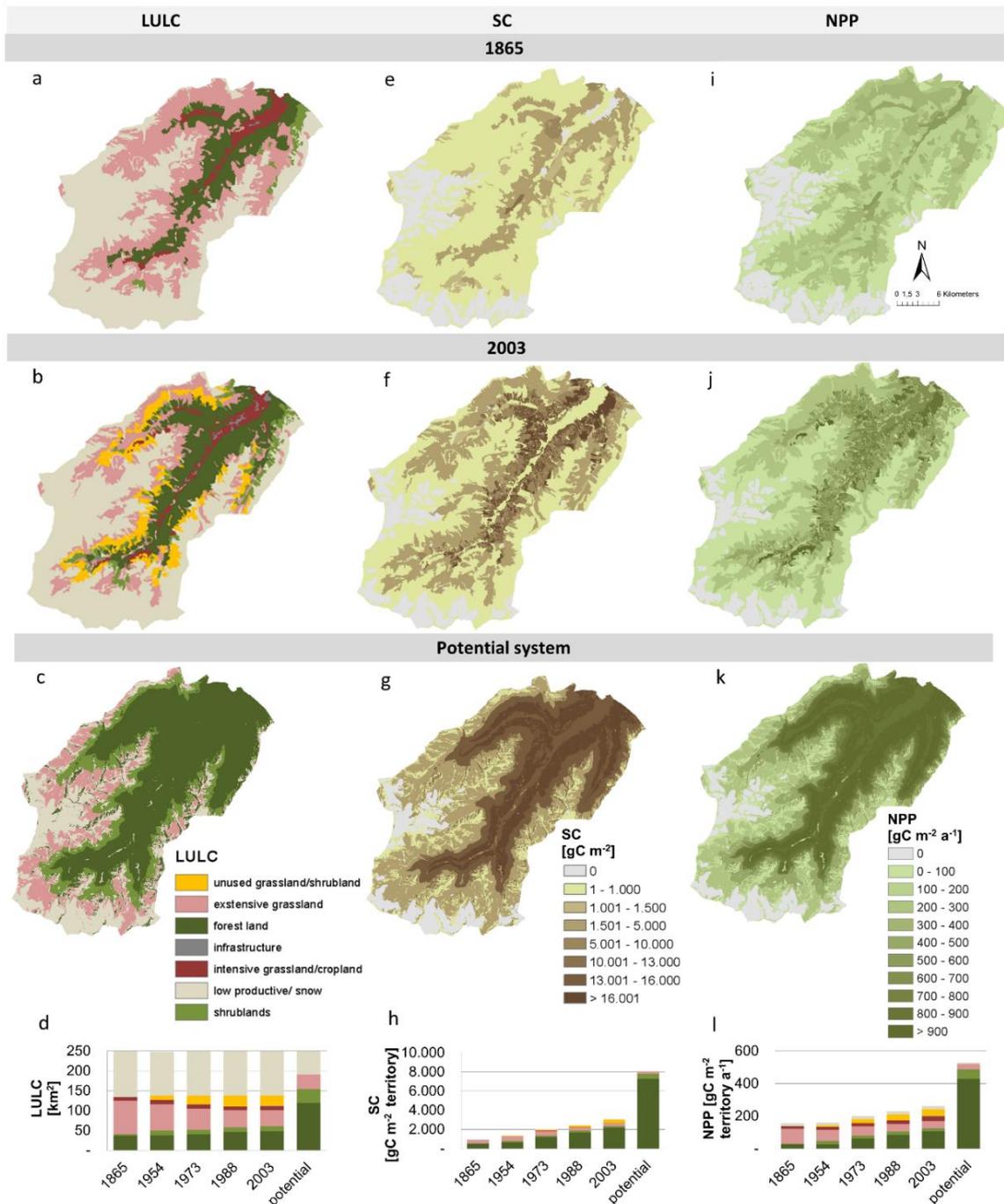


Figure 28: Patterns of LULC (a-c), SC (e-g) and NPP (i-k) in the Stubai-valley. Maps in the first row show patterns for the year 1865, the second row for 2003 and the bottom maps show the potential land system. (d) Trends of LULC changes for all time cuts (1865, 1954, 1973, 1988, 2003) broken down to the main LULC-classes, (h) SC and (i) NPP values for all time cuts normalized by the total study area. Color codes of the LULC legend (c) matches the color codes of d, h and l (the figure is taken from Niedertscheider et al., 2017, see <https://link.springer.com/article/10.1007/s10021-017-0120-5>, open access).

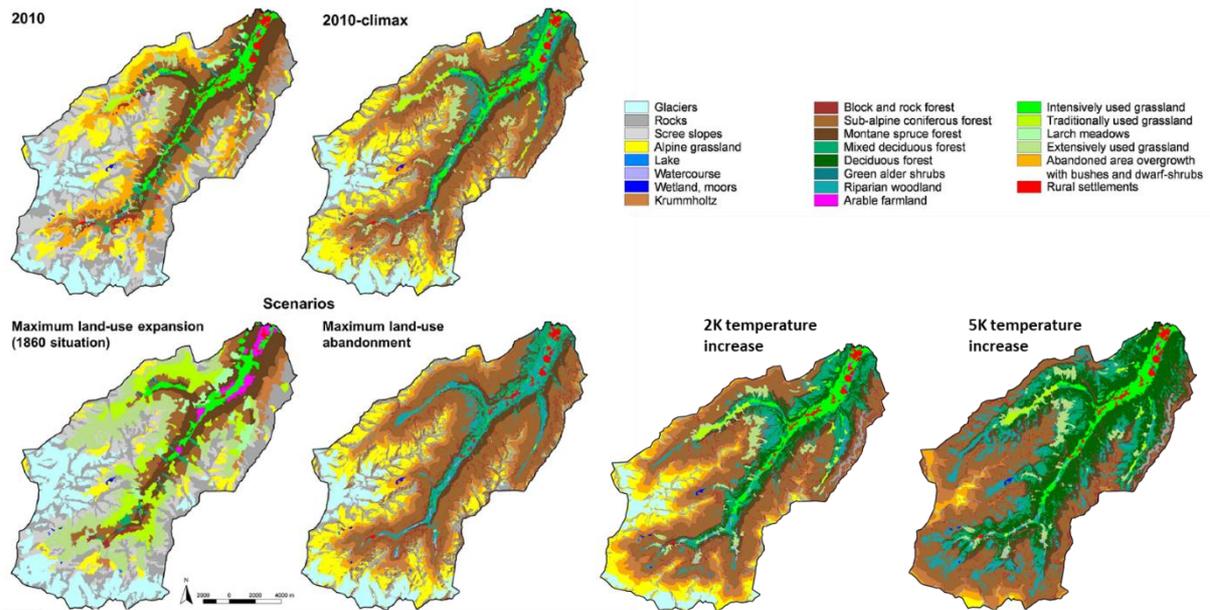


Figure 29: Historical and future developments in LULC distribution as a result of land-use and climate changes starting from current conditions concerning land use (after recovery succession) and climate in the Stubai valley. The scenario 'maximum land-use expansion' corresponds to LULC distribution in 1860 (after Tasser et al. 2017).

These findings are crucial for the understanding of C-dynamics, including the role of land management and time-lags in mountainous regions, which are regarded key areas for terrestrial C-sequestration.

In a second paper (Tasser et al. 2017) we assessed for the study region Stubai Valley (1) the historical and likely future spatial patterns of land use/land cover, (2) the influence of temperature increase on the LULC distribution, and (3) the speed at which these changes will occur. Based on the historical landscape development and spatially explicit models, the effects of various land use and climate scenarios were modelled. Employing a pan-Alpine model, we were able to detect the temporal trajectory of spatial reforestation (Fig. 29). The results show that land-use changes that already occurred during the last decades are responsible for the main future land use/land cover changes (by secondary succession). Only an extreme land abandonment scenario and extreme climate scenarios (5K temperature increase) would bring about similar changes in land use/land cover distribution and expansion of the forested areas. While alpine grasslands, alpine pioneer formations and glaciers would shrink drastically, especially deciduous forests would spread. To a considerable degree, such changes might take place over the next 300 years. By contrast, the increase in forest areas triggered by temperature changes would be slower and longer termed (up to 700-800 years).

5.2 Importance of climate, management and natural disturbances on forest regulating ecosystem services

The second sub-workpackage was completed in 2018 in close cooperation with Rupert Seidl. It aimed at assessing the relative importance of climate, management as well as natural disturbances on forest regulating ecosystem services (RES) in the Stubai valley. Specific aims were (i) to quantify future RES supply, (ii) to determine the relative influences of climate change, management and natural disturbances on future RES variation, and (iii) to identify priority areas for ecosystem management based on land-use legacies and site conditions. To this end, future forest development under different climate, management, and disturbance scenarios as well as the resulting changes in RES supply was quantitatively studied using iLand, the individual-based forest landscape and disturbance model (Seidl et al. 2012a). The modelling work was finalized in December 2018, allowing for a submission of the paper to “Forest Ecology and Management”. The results indicate that both positive and negative climate change impacts are possible. The impacts depend also on the severity of future climate changes and the RES considered. Furthermore, it could be shown that unmanaged forests are efficient in RES provision, but areas where past land-use legacies are still very important have a lower potential to be influenced by management. The spatial explicit results for the whole forested area in the Stubai valley will allow stakeholder to base future ecosystem management on an evidence-based combination of natural ecosystem dynamics and active interventions.

5.3 Conclusions

Despite these novel findings and the substantial empirical efforts, our analysis did not allow providing strong evidence on systemic linkages between extreme events and land-use shifts in a long, historic time series approach. Two reasons are responsible for this:

(a) the temporal resolution of the historical socio-economic data, in our case on land use/land cover, and in particular the spatially explicit data set is too low to link immediate land-use changes to extreme events. Despite massive efforts, it was not possible to construct more than five time steps between 1865 and 2003. The occurrence of extreme events, in contrast, is punctual, even if it affects large areas, so that society can recover land-use systems. The data set used did not match a single reported extreme event such as avalanches, wind throws or fire events.

(b) Societies and their interaction with natural processes have co-evolved over time. Thus, society and, in particular, land use, is adapted to a certain regime of extreme events, related e.g. to the frequency and severity, but also the location of events. In other words, re-occurring summer droughts, avalanches, landslides or forest fires have affected the way society uses terrestrial ecosystems ever since, and society developed adaptation and mitigation strategies to cope with the assemblage of timing, frequency, intensity etc. of extreme events. Hence, societies have developed resilience against an extreme events regime, which might have acted as a buffer and did not result in significant or detectable land-use shifts. Examples for such strategies (or buffers) are the

establishment of protection forests in parcels of high avalanche risks, or irrigation infrastructure for agriculture during drought periods. These two aspects render attempts to link land-use changes to the occurrence of extreme events intricate. But the insights gained in the project allow to sketch out a major research direction and scientific challenge related to socio-ecological extreme events research. The challenge is, conceptually in consequence of point (b), and empirically in consequence of point (a) not to identify and characterize extreme events per se (in the sense of events that are outside the statistical range of occurrences). Rather, the challenge involves advancing the understanding of extreme event regimes and the social adaptation processes. This must include aspects such as (statistical) characteristics, variability, or trajectories of extreme events, as well as social and socioeconomic adaption and mitigation mechanisms. Ensuing, the identification of thresholds and transition phases that mark changes in such regimes and result in directly and indirectly induced land use changes must be in the heart of future research. In the light of accelerating climatic extreme events, the identification and development of tools that allow anticipating tipping points in socio-ecological systems will be crucial. These considerations are further developed and contextualized in a paper project emerging from a Future Earth workshop held in 2017 (Thonicke et al., submitted).

6. Publications, Theses and Follow-up Activities

6.1 Publications

- Anadon-Rosell A, Hasibeder R, Palacio S, Mayr S, Ingrisich J, Ninot JM, Nogués S, Bahn M (2017) Short-term carbon allocation dynamics in subalpine dwarf shrubs and their responses to experimental summer drought. *Environmental and Experimental Botany* 141: 92-102.
- Bahn M, Ingrisich J (2018) Accounting for Complexity in Resilience Comparisons: A Reply to Yeung and Richardson, and Further Considerations. *Trends in Ecology & Evolution* 33: 649-651.
- Harris E, Ladreiter-Knauss T, Butterbach-Bahl K, Wolf B, Bahn M (2018) Land-use and abandonment alter methane and nitrous oxide fluxes in mountain grasslands. *Science of the Total Environment* 628: 997-1008.
- Hörtnagl L, Barthel M, Buchmann N, Eugster W, Butterbach-Bahl K, Díaz-Pinés E, Zeeman M, Klumpp K, Kiese R, Bahn M, Hammerle A, Lu H, Ladreiter-Knauss T, Burri S, Merbold L (2018) Greenhouse gas fluxes over managed grasslands in Central Europe. *Global Change Biology* 24: 1843-1872.
- Ingrisich J, Bahn M (2018) Towards a comparable quantification of resilience. *Trends in Ecology and Evolution* 33: 251-259.
- Ingrisich J, Karlowsky S, Anadon-Rosell A, Hasibeder R, König A, Augusti A, Gleixner G, Bahn M (2018) Land Use Alters the Drought Responses of Productivity and CO₂ Fluxes in Mountain Grassland. *Ecosystems* 21: 689-703.
- Karlowsky S, Augusti A, Ingrisich J, Hasibeder R, Lange M, Lavorel S, Bahn M, Gleixner G (2018) Land use in mountain grasslands alters drought response and recovery of carbon allocation and plant-microbial interactions. *Journal of Ecology* 106: 1230-1243.
- Karlowsky S, Augusti A, Ingrisich J, Kamal Uddin Akanda M, Bahn M, Gleixner G (2018) Drought-induced accumulation of root exudates supports post-drought recovery of microbes in mountain grassland. *Frontiers in Plant Science* 9: 1593; doi.org/10.3389/fpls.2018.01593
- Niedertscheider M, Tasser E, Patek M, Rüdissler J, Tappeiner U, Erb KH (2017) Influence of Land-Use Intensification on Vegetation C-Stocks in an Alpine Valley from 1865 to 2003. *Ecosystems* 20(8): 1391–1406.
- Stuart-Haëntjens E, De Boeck HJ, Lemoine NP, Mänd P, Kröel-Dulay G, Schmidt IK, Jentsch A, Stampfli A, Anderegg WRL, Bahn M, Kreyling J, Wohlgemuth T, Lloret F, Classen AT, Gough CM, Smith MD (2018) Mean annual precipitation predicts primary production resistance and resilience to extreme drought. *Science of the Total Environment* 636: 360-366.
- Szukics U, Grigulis K, Legay N, Kastl E-M, Baxendale C, Bardgett RD, Clément J-C, Lavorel S, Schloter M, Bahn M (2019) Management versus site effects on the abundance of nitrifiers and denitrifiers in European mountain grasslands. *Science of The Total Environment* 648: 745-753.

Tasser E, Leitinger G, Tappeiner U (2017) Climate Change versus Land-Use Change - which affects the landscape more? *Land Use Policy* 60: 60–72.

Wu D, Ciais P, Viovy N, Knapp AK, Wilcox K, Bahn M, Smith MD, Vicca S, et al. (2018) Asymmetric responses of primary productivity to altered precipitation simulated by ecosystem models across three long-term grassland sites. *Biogeosciences* 15: 3421-3437.

6.1.1 Publications currently in preparation / in review:

Seidl R, Albrich K, Erb KH, Formayer H, Leidinger D, Leitinger G, Tappeiner U, Tasser E, Rammer W: What drives the future supply of regulating ecosystem services in a mountain forest landscape? Submitted December 2018

Thonicke K, Bahn M, Bardgett R, Erb KH, Giamberini M, Lavorel S, Reichstein M, Vollan B, Rammig A: Advancing the understanding of adaptive capacity of social-ecological systems to absorb climate extremes. Submitted January 2019

Bahn M, et al. (in prep.) Drought legacies on soil and ecosystem processes in mountain grassland.

Ingrisch J, et al. (in prep.) Drought effects on ecosystem processes in managed and abandoned mountain grassland.

Oberleitner F, Hasibeder R, Wagner J, Mayr S, Losso A, Hartmann H, Oberhuber W, Wieser G, Bahn M (in prep.) Water use and growth responses of Norway spruce and European larch to experimental drought at the subalpine tree line.

Van Sundert K, Bahn M, Brune B, Hasibeder R, Nijs I, Vicca S (in prep.) Post-drought rewetting Birch effect associated with large mobilization of potassium and plant stoichiometric shifts in a subalpine grassland.

6.2 Presentations

6.2.1 Oral conference presentations

Bahn M (2015) Effects of changing land use and climate on grassland biogeochemistry at the LTER-site Stubai. LTER Austria Conference, Vienna. 18.02.2015 (invited talk)

Bahn M (2015) Ecosystem carbon and nitrogen dynamics in response to climate extremes. Ecology at the Interface: Science-based Solutions for Human Well Being - Joint conference (European Ecological Federation and Italian Society of Ecology), Rome, 24.09.2015 (invited talk)

Bahn M (2015) Effects of changing land use and climate on grassland biogeochemistry in the Austrian Alps. Ecology at the Interface: Science-based Solutions for Human Well Being - Joint conference (European Ecological Federation and Italian Society of Ecology), Rome, 24.09.2015 (invited keynote talk)

- Bahn M (2016) Plant-soil interactions and soil carbon dynamics under climate extremes. European Geosciences Union General Assembly, Vienna, 19.4.2016 (solicited keynote talk)
- Bahn M (2016) Drought legacies on soil and ecosystem processes in mountain grassland. ClimMani-INTERFACE workshop 'After the extreme: Measuring and modeling impacts on terrestrial ecosystems when thresholds are exceeded'. Florence, 14.4.2016 (invited talk)
- Bahn M, Hasibeder R, Fuchslueger L, Ingrisch J, Ladreiter-Knauss T, Lair G, Reinthaler D, Richter A, Kaufmann R (2017) Does drought legacy alter the recovery of grassland carbon Dynamics from drought? European Geosciences Union (EGU) General Assembly 2017, Wien, 26.04.2017
- Bahn M, Hasibeder R, Fuchslueger L, Ingrisch J, Ladreiter-Knauss T, Lair G, Reinthaler D, Richter A, Solderer H, Kaufmann R (2017) Does drought legacy alter the recovery of grassland carbon dynamics from drought? Ecology Across Borders: Joint Annual Meeting 2017, Gent / Ghent, 13.12.2017
- Bahn M, Tappeiner U (2018) ClimLUC: Versuchsansatz und erste Ergebnisse. Jahrestagung der LTSER Forschungsplattform Tyrolean Alps, 26.2.2018
- Gleixner G, Karlowky S, Augusti A, Ingrisch J, Hasibeder R, Lange M, Lavorel S, Bahn M (2018) Resistance and recovery of rhizospheric carbon and nitrogen flow in fungi- and bacteria-dominated plant communities after drought. European Geosciences Union (EGU) General Assembly 2018, Wien, 09.04.2018
- Hörtnagl L, Bahn M, Buchmann N, Dias-Pinez E, Eugster W, Kiese R, Klumpp K, Ladreiter-Knauss T, Lu H, Wohlfahrt G, Zeeman M, Merbold L (2016) The influence of management on GHG fluxes over Central European grasslands. European Geosciences Union (EGU) General Assembly 2016, Wien, 20.04.2016
- Ingrisch J, Karlowky S, Gleixner G, Bahn M (2018) Land use alters drought effects on belowground partitioning of recent carbon in mountain grassland. GfÖ Jahrestagung, Wien, Sep 2018
- Ingrisch J, Hasibeder R, Karlowky S, Gleixner G, Bahn M (2018) Effects of land-use change on the resilience of grassland carbon dynamics to extreme drought. susAlps Conference 2018, 18 – 20 Sep, Garmisch-Partenkirchen; <https://conference2018.susalps.de/>
- Morcote Martinez MC, Ingrisch J, Hasibeder R, Solderer H, Van Sundert K, Vicca S, Bahn M (2018) Tissue stoichiometry as a forage quality index in the context of climate change: drought-related productivity constraints and nutrient quality. 20th Meeting of the FAO-CIHEAM Mountain Pastures subnetwork, Lofoten Island, Norway, 9. - 12.09.2018
- Niedertscheider M, Erb K, Rüdiger J, Tappeiner U, Tasser E (2016) Land system change in an Austrian valley since 1861: Studying carbon dynamics and its implications for the climate system 3rd Global Land Project, Open Science Meeting (GLPOSM16), Beijing, 25.10.2016

Tappeiner U, Bahn M, Leitinger G, Tasser E, Schermer M (2015) Coupling socio-economical and ecological research in the Alps: LTSER site Stubai Valley, Austria. Perth III: Mountains of Our Future Earth, Perth, 05.10.2015

Tappeiner U (2018): Klimawandel und die Konsequenzen für die Landschaft/Les conséquences paysagères du changement climatique. Landschaftskongress / congrès paysage 2018, Luzern, 24.10.2018. (solicited keynote talk)

Tasser E (2018) Positionsbestimmung und Strategien zur Zukunft des Alpenraums. EUSALP 2018 - A cross-disciplinary conference, Innsbruck. 04.04.2018. (solicited talk)

Tasser E (2018) Landschaft und deren Leistungen im Wandel: eine Zusammenschau. TAGUNG.LANDSCHAFT. Zwischen Almen und Metropolen. Landschaft im Alpenraum – Herausforderung oder Dilemma? Innsbruck, 11.-13.04.2018. (solicited talk)

6.2.2 Conference poster presentations

Bahn M, Erb K, Hasibeder R, Mayr S, Niedertscheider M, Oberhuber W, Tappeiner U, Tasser E, Viovy N, Wieser G (2016) Climate Extremes and Land-Use Change: Effects on Ecosystem Processes and Services. European Geosciences Union (EGU) General Assembly 2016, Wien, 18.04.2016. See also: Geophysical Research Abstracts 18, No. 14892

Thonicke K, Bahn M, Bardgett R, Bloemen J, Chabay I, Erb K, Giamberini M, Gingrich S, Lavorel S, Liehr S, Rammig A (2017) Advancing the adaptive capacity of social-ecological systems to absorb climate extremes. European Geosciences Union (EGU) General Assembly 2017, Wien, 28.04.2017

6.2.3 Further presentations

Bahn M (2018) Towards a comparable quantification of resilience. Invited lecture at PhD school on “Resilience of living systems”, Wageningen, 29.04.2018

Bahn M (2018) Grassland carbon dynamics under changing climate and land use. Invited seminar talk, Universität Basel, Basel, 26.04.2018

Oberleitner F, Hasibeder R, Wagner J, Hartmann H, Losso A, Mayr S, Oberhuber W, Wieser G, Bahn M (2019) Water use and growth responses of Norway spruce and European larch to experimental drought at the subalpine tree line. European Geosciences Union (EGU) General Assembly 2019.

Siegl G, Schermer M, Tasser E (2017) Wir LandschaftMacher. Erwachsenenenschule Patsch, Patsch, 20.10.2017.

Tappeiner U (2017) Landschaft im Wandel“ - Wie beeinflussen Menschen und Klimawandel das sensible Ökosystem alpiner Raum? Tag der Sonne, Trins, 5.5.2017. (solicited talk)

Tasser E (2018) Selbstversorgungsgrad und Landnutzung in Tirol. Workshopreihe: Der Zukunft den Boden bereiten. Innsbruck, 16.05.2018. (solicited talk)

6.3 Co-Organization of relevant Conference Sessions

Thonicke K, Bahn M (2016) Adaptive capacity of coupled socio-ecological systems to absorb climate extremes. Future Earth Cross community workshop on Extreme Events and Environments from Climate to Society (E3S). Berlin. 14. - 16.02.2016

Reichstein M, Doetterl S, Bahn M, Luo Y, Frank D, Carvalhais N, Mulder VL, Kaiser M (2016) Climate extremes, ecosystems and dynamic landscapes controlling biogeochemical cycles. European Geosciences Union (EGU) General Assembly 2016, Vienna, 17.04.2016 - 22.04.2016

Reichstein M, Bahn M, van Emmerik T, Hegerl G, Seneviratne S, Sillmann J, Frank D, Green J (2017) Climate extremes, biosphere and society: impacts, remote sensing, and feedbacks. European Geosciences Union (EGU) General Assembly 2017, Vienna, 28.04.2017

6.4 Theses contributing to ClimLUC

6.4.1 Master Theses

Brune V (2018) Impacts of an extreme summer drought on soil respiration in mountain ecosystems differing in land use. Master Thesis, University of Innsbruck, 86 p.

Hölzl A (2016) Klima-Wachstums-Beziehung von Nadelgehölzen im Waldgrenzökoton Kaserstattalm (Stubaital, Tirol). Diploma Thesis, University of Innsbruck.

Krismer H (2018) Reaktion von Baumzuwächsen auf Trockenjahre in den Bergwäldern des Stubaitals. Master Thesis, Universität für Bodenkultur, Vienna, 86 p.

Morcote-Martinez MC (in prep) Drought effects on leaf and root stoichiometry in managed and abandoned mountain grassland. Master Thesis, University of Innsbruck.

Oberhofer L (2018) Funktionserfüllung relevanter Waldbestände im Stubaital unter aktuellem Klima und mögliche Auswirkungen hinsichtlich Klimaänderungen. Department für Wald- und Bodenwissenschaften, Institut für Waldbau, Universität für Bodenkultur, Vienna.

Pirchmoser S (in progress) Influence of drought on vegetation composition and phenology. Master Thesis, University of Innsbruck.

Solderer H (2018) Impacts of recurrent drought on CO₂ and water vapour fluxes and primary production in mountain grassland. Master Thesis, University of Innsbruck, 47 p.

Wagner J (in progress) Impact of extreme summer drought on radial growth and sapflow of *Picea abies* and *Larix decidua*. Master Thesis, University of Innsbruck.

6.4.2 Bachelor Theses

Drexler L (2018) Auswirkung von Sommerdürre auf den Netto-CO₂-Austausch (NEE) einer Almbrache. Bachelor Thesis, University of Innsbruck, 35 p.

Flucher S (2017) Auswirkungen von Sommerdürre auf den CO₂-Austausch unterschiedlich bewirtschafteter Graslandsysteme im Gebirge. Bachelor Thesis, University of Innsbruck, 33 p.

Haidegger M (2018) Auswirkungen von Sommerdürre auf den CO₂-Austausch einer Bergmähwiese. Bachelor Thesis, University of Innsbruck, 41 p.

Höllner J (2017) Dendroökologische Untersuchung von Fichtenbeständen entlang eines Höhentransekts im Stubaital. Bachelor Thesis, University of Innsbruck, 69 p.

Kiessling A (2018) Response of root length and hyphal length to single and recurrent drought events at a subalpine meadow in the Stubai Valley in Austria. Bachelor Thesis, University of Innsbruck, 27 p.

Pircher-Nöckler ER (2017) Dendroökologische Untersuchung von Lärchenbeständen entlang eines Höhentransekts im Stubaital. Bachelor Thesis, University of Innsbruck, 67 p.

Wagner J (2016) Radiale Zuwachsdynamik von Fichte (*Picea abies*) und Lärche (*Larix decidua*) in einer subalpinen Aufforstungsfläche im Stubaital. Bachelor Thesis, University of Innsbruck, 25 p.

6.5 Follow-up Activities

The grassland sites and the new forest site, established with the help of the ClimLUC project, have been included in the successful application for the infrastructure project LTER-CWN (Long-Term Ecosystem Research Infrastructure for Carbon, Water and Nitrogen), funded by the Austrian Research Promotion Agency FFG (2017-2022) (<https://www.lter-austria.at/en/cwn-project/>). The project is co-ordinated by the University of Vienna and involves five other long-term sites across Austria.

ClimLUC results have contributed to the EuregioLAB 2018 “Natural hazard management and biodiversity” which has been presented on the occasion of the Tyrol Day of the European Forum Alpbach and has been discussed with the president of the Forum Alpbach and the governor of South Tyrol and the Vice governor of Tyrol.

ClimLUC results will be included in the new Austrian Assessment Report of the Austrian Panel on Climate Change by Michael Bahn and Ulrike Tappeiner.

Furthermore, three proposals for follow-up research projects have been submitted. Two are still in review, and the following project has meanwhile be funded by the Austrian Science Fund (FWF): NitroTrace: Using isotopes to trace the effects of climate extremes on N₂O emissions and the nitrogen cycle in managed grasslands (2018-2021, PIs Eliza Harris and Michael Bahn).

As an important follow-up outreach activity, three dedicated workshops will be convened by Michael Bahn, Stefan Mayr and Ulrike Tappeiner, contributing to the International Mountain Conference 2019 in Innsbruck.

7. References

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