Community specific hydraulic conductance potential of soil water decomposed for two Alpine grasslands by small-scale lysimetry

Georg Frenck[ab], Georg Leitinger[ab], Nikolaus Obojes[a], Magdalena Hofmann[b], Christian Newesely[b], Mario Deutschmann[b], Ulrike Tappeiner[ab] & Erich Tasser[a*]

[a] Institute for Alpine Environment, EURAC research, Viale Druso 1, 39100 Bozen/Bolzano, ITA

[b] Institute of Ecology, University of Innsbruck, Sternwartestrasse 15, 6020 Innsbruck, AUT

Correspondence to: Erich Tasser (erich.tasser@eurac.edu)

Abstract: For Central Europe in addition to rising temperatures an increasing variability of precipitation is predicted. This will increase the probability of drought periods in the Alps, where water supply has been sufficient in most areas so far. For Alpine grasslands, community specific imprints on drought response are merely understood. In a replicated mesocosm experiment we compared evapotranspiration and biomass productivity of two differently drought-adapted vegetation communities during two artificial drought periods divided by extreme precipitation events using high precision small lysimeters. The drought adapted vegetation type showed a high potential to utilize even scarce water resources combined with a low potential to translate atmospheric deficits into higher water conductance with biomass production staying below those measured for the non-drought-adapted type. The non-drought-adapted type, in contrast, showed high water conductance potential with strongly increasing ET rates when environmental conditions became less constraining. With high rates even at dry conditions, this community appears not to be optimized to save water and might experience drought effects earlier and probably stronger. In summary, the vegetation's reaction two co-varying gradients of potential evapotranspiration and soil water content revealed a clear difference of vegetation development and between water-saving and water-spending strategies regarding evapotranspiration.

26   Comprehensive alterations in the climate system of the earth are projected for the future decades. Due to increased
27   greenhouse gas concentrations in the atmosphere, the global average temperature is predicted to rise. These changes in the
28   energy budget of the atmosphere are suggested to propagate alterations in atmospheric circulation and modify precipitation
29   patterns worldwide (IPCC, 2013; Knapp et al., 2008; Solomon et al., 2009). Such variations can result in changes of the
30   spatial distribution of precipitation and thereby affect average values of rainfall locally. However, concurrent changes in the
31   temporal occurrence are predicted to increase the variability of rainfall with longer intervals in between and more extreme
32   events. This will lead to stronger variability in soil water availability and longer droughts (IPCC, 2013, 2012).

33   The water balance in terrestrial ecosystems is dominantly controlled by plant processes. It is suggested that up to 80%
34   of the terrestrial water loss to the atmosphere is mediated through plant transpiration(Jasechko et al., 2013). Consequently, it
35   is assumed that plants will experience drought stress more frequently, which may constrain primary productivity as the latter
36   is substantially controlled by the supply of water (Knapp et al., 2008). These direct effects of limited water provision to the
37   system will be accompanied by increased water demand in a warmer world, leading to more negative water balances, which
38   will accentuate drought effects on vegetation processes (Heimann and Reichstein, 2008). However, structure and
39   functionality of the ecosystems - defining rates of evapotranspiration - are also subject to local climatic conditions. Hence, a
40   direct feedback mechanism is established, which might amplify or dampen the global and local consequences of climatic
41   change on ecosystems (Heimann and Reichstein, 2008).

42   Defining productivity-precipitation relationships of ecosystems is of focused interest, because structural changes in
43   soil-plant-atmosphere interface, which control water fluxes into the atmosphere will inherently be affected by the
44   manifestation of that relationship. However, beyond the direct implications of limited water availability on biomass
45   production and growth, the composition of individual plant species in the community and resulting functional structure of
46   that community will adjust, optimising water use according to different life-history strategies by competitive interactions
47   (Peñuelas et al., 2004). In turn, immediate vegetation responses to fluctuations in precipitation patterns and the strength of
48   interaction with productivity functions will strongly depend on the functional composition of the community and ecosystem
49   considered. Therefore, intrinsic characteristics of vegetation will impose another layer of complexity for defining the
50   interactive feedbacks in the relationship between water budget and productivity.

51   The impact of shifting precipitation regimes can be predicted only inaccurately if the crucial components of the
52   ecosystem water budget - soils, plants and the atmosphere - are evaluated separately and isolated. Due to the complex
53   interactions and processes at different spatio-temporal scales the response of ecosystems to shifts in the water regime are
54   preferably examined in an integrative manner on the system level (Silva, 2015). Manipulative experiments are a well suited
55   option for investigating the effects imposed by changes in precipitation frequency and intensity below and above the natural
56   range on the ecosystem level (Estiarte et al., 2016). Since we currently lack knowledge needed to validate the projections for
57   consequences of future changes in rainfall regimes, insights from such integrative investigations are highly valuable for
58   providing important benchmarks of model based assessments (Estiarte et al., 2016).

59   Numerous studies were performed to reveal the response of temperate grasslands to climatic changes and extremes,

60   while only few investigations targeted Alpine systems (De Boeck et al., 2016). While the Alps did not often experience

61   droughts during the past (van der Schrier et al., 2007), the region has undergone exceptionally fast climatic changes during

62   the late 19th through early 21st century (Auer et al., 2007; Beniston, 2005; Böhm et al., 2001; Ciccarelli et al., 2008; Rebetez

63   and Reinhard, 2008). Considering the fundamental role Alpine systems have to water accumulation and freshwater supply

64   for large parts of Europe (Messerli et al., 2004; Viviroli et al., 2003) it seems surprising that the responses of ecosystems in

65   the Alps to changes in precipitation have not drawn more scientific attention. However, while projections suggest only

66   moderate variations of yearly average rainfall in the Alps, significant alterations within the temporal occurrence of rainfall

67   events with a decrease in summer precipitation and increases from winter through spring are implied (Beniston, 2012;

68   Beniston et al., 2007). The decrease of water supply during warmer summer months will potentially increase the frequency

69   and intensity of drought events in the near and longer future in Alpine ecosystems (Gobiet et al., 2014).

70   For unravelling ecosystem water fluxes at the soil-plant-atmosphere interface, the lysimeter methodology provides the

71   precise and realistic means by allowing to decompose the driving sub-processes: evapotranspiration (ET), precipitation (P)

72   and drainage below the rooting zone (Peters et al., 2014). By avoiding systematic errors prone to traditional measurement

73   systems, the determination of the net water balance is highly accurate and robust (Schrader et al., 2013). If embedded into a

74   surrounding ecosystem, automated lysimeter units, which do not need access to perform manual weighing, measure water

75   fluxes with a minimum of disturbance to the natural boundary layer and microclimatic conditions. Such implementations of

76   autonomous weighable high precision lysimeters provide unprecedented realism to the description of ecosystem water

77   balances, especially when filling of the lysimeters was performed to maintain natural soil layering and the connectivity of

78   pores, while keeping potential impacts on the vegetation community low. Over the recent years, several of these units have

79   been established over Europe, e.g. a network of 126 lysimeters at 12 sites has been established to monitor climate chance

80   induced alterations in hydrological cycling within the TERENO project in Germany (Bogena et al., 2006; Zacharias et al.,

81   2011). However, the large dimensions (1m diameter/ volume) and the corresponding economic efforts for their establishment

82   did mostly eliminate the possibility for replicated manipulative experiments employing fully integrated lysimeters.

83   In a common garden experiment we used a network of automated small scale lysimeters to emerge community

84   specific differences in the temporal dynamics of soil water depletion and evapotranspiration. Two different Alpine grassland

85   communities were subjected to contrasting levels of water availability. Sheltered from natural precipitation, soil water

86   content was manipulated by applying two distinct irrigation regimes: one providing water in regular intervals and another

87   exposing the corresponding experimental units to extended periods of drought. The natural variability in the atmospheric

88   demand of water vapour coupled to the manipulated water availability in the soil allowed to investigate and reveal vegetation

89   specific conductance properties and water utilisation patterns. For this study we hypothesize that the vegetation adapted to

90   local, humid conditions and characterized by high biomass and a water spending strategy will keep transpiration rates high

91   while soil water availability is decreasing until a sudden decline near wilting point. As a consequence it will also continue to

92   produce biomass until the break point. In contrary, the water saving strategy of the drought-adapted vegetation will lead to a

93   continuous decrease of transpiration and biomass production with decreasing soil water availability.

2.1   Characteristics of the experimental field site and lysimeter installation

95   The study site of the experiment was established during early summer 2014 in the LTER-Austria site 'Stubai' (valley

96   bottom meadow) Neustift im Stubaital (A). The site for the garden-experiment was located on the valley floor at 972 m a.s.l.

97   (WGS84: N47.115833, E11.320556) in a meadow used for hay production.

98   **Table 1 Summary of site conditions and vegetation properties**

site	Stubai (S) – study site location	Matsch/Mazia (M) – transplant origin
municipality	Neustift im Stubaital, Wipptal/Austria	Mals/Malles, Vinschgau/Italy
elevation/ altitude (m a.s.l.)	970	1570
longitude/ latitude	47°07'05''N 11°19'17''E	46°41'19''N 10°34'42''E
average temperature (°C)	6.5	6.6
average precipitation (mm)	1097.0	526.7
growing season length (no of days with average temperature of at least 5 °C)	224	190
land-use	hay meadow/ 3cuts per yr/ fertilized with cow dung	hay meadow/ 2cuts per yr/ fertilized with cow dung
soil type	gleyed Camisol (A-Bv-Go)	Camisol (Ah-Bv-C)
classification	loamy sand to sandy silt	loam to sandy loam
phytosociological classification	Poo trivialis - Alopecuretum pratensis (Regel 1925)	Ranunculo bulbosi-Arrhenatherum (Ellmauer)
species inventory (responsible for 90% of total plant cover in the lysimeter)	*Achillea millefolium, Carum carvi, Pimpinella major, Poa trivialis, Ranunculus acris, Rumex acetosa, Taraxacum officinale, Trifolium pratense*	*Achillea millefolium, Anthoxanthum odoratum, Anthriscus sylvestris, Carum carvi, Festuca rubra, Leontodon hispidus, Lotus corniculatus, Poa trivialis, Primula veris, Taraxacum officinale, Trifolium montanum, Trifolium pratense, Veronica officinalis*

99

100   For this experiment six plots of 3.5 × 3.5 m were established. Traversing the corresponding area, each plot was

101   defined by installing half-cylindrical metal frames. In the centre of each plot these frames providing the base for the rain

102   sheltering reached a height of approx. 2.5 m. In each corner at the outer plot margin four irrigation sprinklers pointing

103 towards the centre of the plot were set up. The irrigation system described in detail by (Newesely et al., 2015) was used to

104 simulate precipitation during periods of experimental manipulation of water provision to the system.

105   In the centre of each plot two small-scale lysimeters with 0.3 m diameter were installed in collaboration with, and

106 supervised by the employees of the manufacturer (Smart-Field-Lysimeter, UMS/Meter Group Munich, Germany). Every

107 lysimeter was filled with a soil-vegetation monolith by cutting the hollow cylindrical lysimeter blank into an undisturbed

108 patch of the corresponding ecosystem. This compression free procedure allowed to remain the original and unaffected

109 stratification of the soil and to conserve the natural composition of pore spaces within the monolith. The filled lysimeter

110 blanks were subsequently excavated and cut horizontally at a depth of 0.3m. The bottom of the lysimeter was closed with a

111 tension controlled hydraulic boundary connected to a bi-directional pumping system to regulate water flow into and out of

112 the lysimeter. After inserting soil moisture, temperature (EC-5 Small Soil Moisture Sensor, Decagon Devices, USA) and

113 matrix potential probes (MPS-2, Decagon Devices, USA) at 0.05, 0.15 and 0.25m depth into the lysimeter monolith, each

114 system was placed on a weighing platform (accuracy of 0.005 kg, PL-50, UMS/Meter Group Munich, Germany). Two of

115 these lysimeter units were installed in the centre of every experimental plot within a two by two quadratic grid of 1.2m edge

116 length with their relative position to each other assigned randomly.

117   The two monoliths in every plot were excavated from different types of vegetation, one containing a mesocosm of the

118 meadow surrounding the experimental field site (S, Table 1), and another one which was excavated and transplanted from

119 Matsch/Mazia with contrasting environmental and biotic properties to those of the study site (M, Table 1). The Stubai

120 grassland is classified as Poo trivialis - Alopecuretum pratensis with a community of low complexity: abundant Poaceae

121 accompanied by some herb species (Wohlfahrt et al., 2008). The meadow is actively managed, cut two to three times each

122 year and fertilized with cow manure in spring and autumn (approximately 0.35 kg dry matter per m², Table 1). The local

123 climate is dominated by high total precipitation values, especially in the summer. The vegetation of second origin

124 (Matsch/Mazia) is characterised by the traditional, more extensive use of the corresponding system. The Matsch Valley has a

125 dry inneralpine climate with a mean precipitation of 527 mm per year and a mean temperature of 6.6 °C (Hydrographical

126 Department of the Autonomous Province of Bozen-South Tyrol). The vegetation is a dry hay meadow (Ranunculo bulbosi -

127 Arrhenatherum, Ellmauer) on loam to sandy loam. The site is fertilized with cow dung and cut two times each year. The

128 excavation location of the replicate lysimeters was optimized according to the presence of representative and joint species in

129 the respective vegetation patches. After installing the local and transplanted lysimeter mesocosms during early summer 2014

130 into the experimental plots, the vegetation surrounding the lysimeters could recover from disturbances of necessary soil

131 works required to wire the fully automated measuring system until spring 2015.

132   At the field site, all experimental plots and the vegetation in the lysimeters was managed (cut, fertilized) concurrently

133 to land-use scheme of the surrounding meadow. The experimental period started in the last third of June 2015 during the re-

134 growth interval after the first cut at the beginning of June. With beginning of the experiment rain shelters were closed using a

135 UV permeable transparent polythene film (Lumisol Clear AF, 88% - 92% light transmittance). In order to avoid shielding of

136 the wind and to allow the establishment of natural boundary conditions, shelters were left open on the sides facing the main

137 wind direction and closed down to just 0.5 m above the soil level on the lateral sides. Over a period of 52 days the plots of

138 the experiment were subjected to control watering within the two different irrigation schemes (Fig. 1). Concurrently with

139 closing of the rain shelters precipitation was provided from the irrigation sprinklers mimicking average rain fall amounts and

140 intensities for the 30 year period between 1970 through 2000 in the treatment with regular watering. However, due to a

141 mistake by the technician responsible for setting up the automated irrigation protocol the watering scheme stayed below the

142 intended amounts for approximately the first half of the experimental period making manual compensation occasionally

143 necessary. Automated irrigation was programed to occur around mid-night in order to avoid immediate transpiration from

144 the surface and allow the provided water to penetrate into the soil compartment. Manual adjustments and checks on the

145 precipitation simulator were usually performed during day-time. The lysimeter mesocosms in the treatments with regular

146 watering (REG) received approx. 117 kgH2O per m², those in the treatments with extended drought periods an average of 65

147 kg_{H2O} per m² throughout the duration of the experiment and according to the scheme presented in Fig. 1.

148

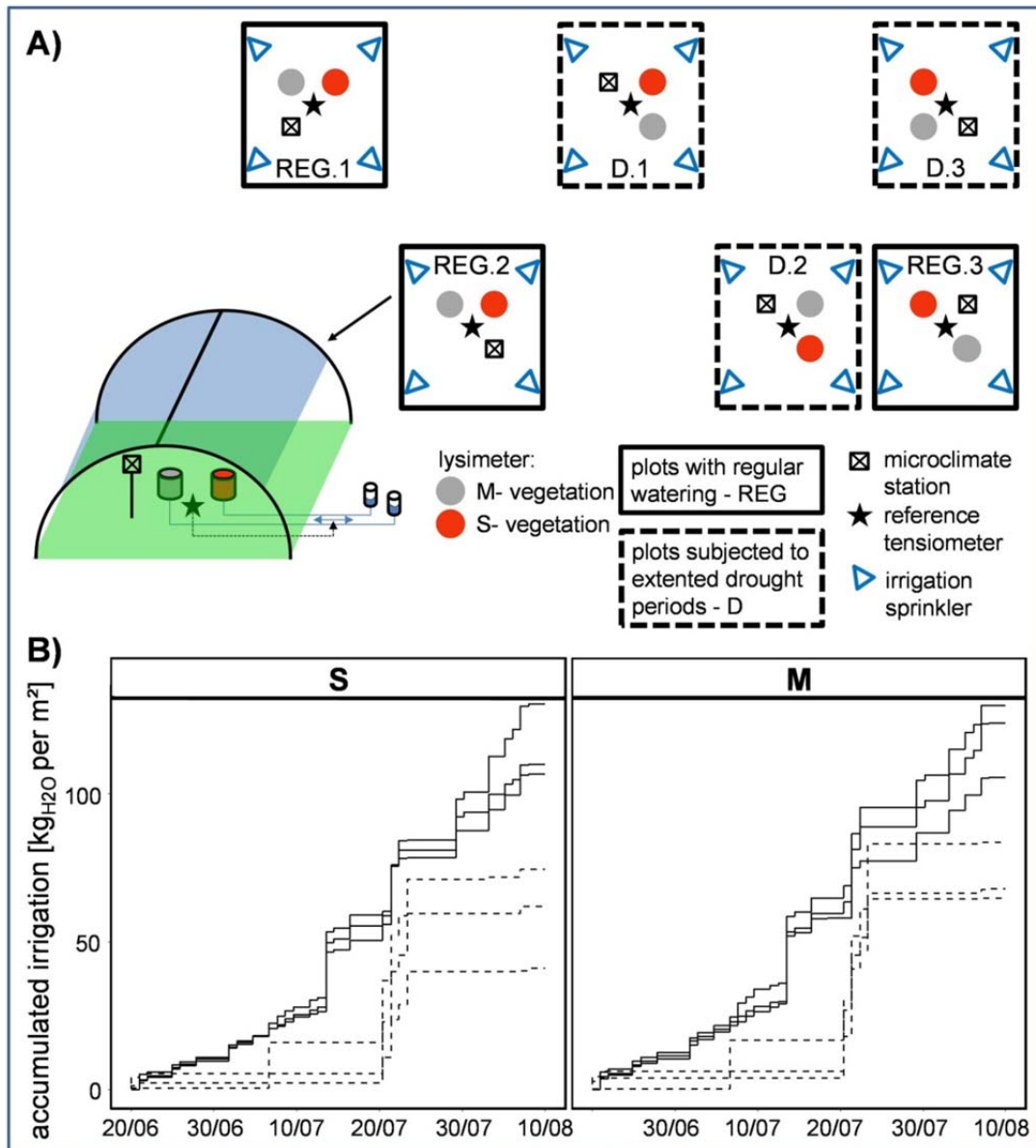



Fig 1: A) Schematic overview of the experimental design and plot setup; B) Manipulation of water availability for individual lysimeters of the two vegetation types (Stubai (S) & Matsch/Mazia (M)) by contrasting irrigation schemes - one providing water on a regular basis (REG, solid lines), one with extended drought periods (D, dashed lines)

152

2.2 Automated measurements

In the centre of each of the six plots a microclimate station measuring air temperature and relative humidity (height: 1m; U23-002 HOBO® External Temperature/Relative Humidity Data Logger, Onset Computer Corporation, USA), solar radiation (height: 1m; S-LIB-M003, Solar Radiation Sensor, Onset Computer Corporation, USA), wind speed (height: 1 m; DAVIS® Standard Anemometer 7911, Davis Instruments, USA) and soil water content 0.05 and 0.2m below the ground (S-SMA-M005, Soil Moisture Smart Sensor – 0.2 m ECH2O® probes, Decagon, USA) was installed. The corresponding measurements were logged for every ten minutes interval (HOBO Microstation® Data Logger; Onset Computer Corporation, USA).

For each of the lysimeter, weight data were recorded every minute, data received from matric potential, soil temperature and water content sensors (each in 0.05, 0.15 and 0.25 m depth) in ten minutes intervals. The hydraulic boundary at the bottom of each lysimeter was connected to a reservoir of drainage water with the corresponding container also being placed on a balance. A bi-directional pumping system allowed the adjustment of the water content at the lower boundary of the lysimeter by transferring water either from the drainage container into the lysimeter or the contrary direction. This implementation allowed to adjust the water levels at bottom of the lysimeter according to a reference matric potential measured at the same depth in the natural unaffected soil column of the respective experimental plots.

2.3 Manual measurements of biomass development

Since variation in total water flux from vegetation canopies to the atmosphere is a product of the variation in standing biomass and the water vapour release per unit biomass decomposing and addressing these two factors is advisable, especially in replicated experiments or when communities with different biomass progression rates are being compared over longer periods. However, non-destructive biomass estimation of complex stands in the field can be challenging with respect to desired accuracy. In order to generate robust estimates different methodologies were combined in current experiment. Measurements of maximum and average canopy height (Machado et al., 2002) were supplemented with a pin point procedure (Jonasson, 1988) and measurements of projected area (Lati et al., 2013) for the estimation of biomass present in the lysimeters. For measuring pin contacts a thin metal rod was lowered through a plate placed above down to the lysimeter. Pin measurements were replicated in seven (out of 21) randomly assigned positions for each lysimeter and point in time. Pin contacts were referenced within three height classes (0-20, 20-40, 40+ cm above the ground) and by functional group identity of the plants. For the determination of projected area of the lysimeter canopies the methodology proposed by Tackenberg (2007) was adapted. Digital images of the lysimeter stands in front of a white half-cylindrical background were scaled according to a size standard in each picture, converted to a black-white colour scheme, before black pixels were enumerated. On average, biomass of the lysimeters was estimated for every third day through the period of the experiment. The different methods for non-destructive biomass estimation were calibrated against weighted biomass at the harvests prior

185   and subsequent to the experiment. Based on these calibrations the biomass development in the lysimeters was predicted

186   throughout the experimental period.

187

2.4   Data processing and statistics

189   To calculate the water mass fluxes at the soil-vegetation-atmosphere interface of the upper lysimeter boundary,

190   weight differentials of the drainage reservoir and the lysimeters were summarized and subsequently cleared for spikes and

191   signals of implausible strength (Schrader et al., 2013). The latter was necessary because the sensitive weighing elements are

192   susceptible to environmental noise or accidental interference by other experimental proceedings (e.g. biomass estimation),

193   while providing a high accuracy and temporal resolution. The combined weight signal was separated into irrigation induced

194   weight gain of the lysimeter units and weight loss caused by evapotranspiration from the upper lysimeter boundary based on

195   the recorded activity times of the precipitation simulator. Subsequently, daily totals were calculated for both mass

196   differentials.

197   A soil-specific calibration of the soil moisture and the MPS-2 sensors sensor is a necessary prerequisite for a sensor to

198   achieve its highest degree of absolute accuracy in soil water content (SWC) measurements. A substrate moisture retention

199   curve (pF vs. volumetric water content) and the hydraulic conductivity as a function of pF (log10 of the matric potential)

200   were determined for both types of soil-vegetation monoliths (M, S). The soil hydraulic parameters were determined in the

201   laboratory, using the method of (Schindler, 1980) with the HYPROP system (UMS/Meter Group Munich, Germany). Using

202   the soil specific moisture retention curve, absolute SWC was corrected based on soil matrix potential data. To summarize the

203   time course of water availability in the soil of each lysimeter unit, the average values of SWC of both layers between 0.05 -

204   0.15m and 0.15 – 0.25m were integrated and summarized on a daily basis.

205   The evaporative demand of the atmosphere is expressed by the reference crop evapotranspiration (ET_0). It represents

206   the evapotranspiration from a standardized vegetated surface and was calculated in this study after the FAO Penman-

207   Monteith standard method (Allen et al., 1998). ET_0 integrates the most important atmospheric components (solar radiation,

208   temperature, VPD and wind velocity) defining the atmospheric water demand. Daily averages were used as a summed up

209   explanatory parameter to capture the atmospheric draw of water vapour from the lysimeter vegetation for further analysis.

210   Non-destructive estimates for the standing biomass in the lysimeters were calibrated at the harvests before and after

211   the experimental period. Nine different regression models were generated for the different estimation techniques individually

212   and in combinations (appendix 1). Based on the prediction of these models biomass was estimated for every measurement

213   (total of 16) during the experiment. Generating a consensus time-course for the biomass development in every lysimeter a

214   general additive mixed model smoother was fitted for each unit (gamm-function in the mgcv-package, R Development Core

215   Team, 2015) with the different prediction methodologies defining random (observer) - effects. In order to generate a more

216   conservative pattern, the flexibility of the time course defined with these smoothers was constrained by allowing a maximum

of five knots for these smoothers. Based on these models, standing biomass was predicted on a dry weight basis for every lysimeter entity and each day of the experiment.

All statistical analysis presented here were performed using the R statistical programming language(R Development Core Team, 2015). For the evaluation of evapotranspiration responses mixed effects models were fitted using the *nlme*-package. These models included the identity of the different vegetation types (categorical) in full factorial combination with additional covariates defining the fixed part of the model. To reveal the drivers of variation in daily ET rates and separate the effects of variability in biomass (DW –dry weight) and evapotranspiration rates per unit biomass (ET/DW) among the different monoliths a log-log-scaling method was applied on the formula $ET = ET/DW \times DW$ based on the methodology provided by (Renton and Poorter, 2011). For summarizing the time courses of SWC and ET_0 the day of the experiment and the two irrigation schemes were considered as additional categorical variates. For modelling the response surface of ET along the two dimensions of ET_0 and SWC, the latter and all possible interactions with vegetation type were defined as continuous covariates for the fixed part of the model. However, all models included a random intercept for the experimental plot in which the data were collected. Nested within the random effect for the plot, the lysimeter identity was included as another random effect to fully represent the dependence structure in the hierarchical design of the experiment. Were they were found to significantly improve the model fit, lysimeter specific response to continuous covariates in the fixed part were included as random slopes. Further, to account for autocorrelative errors according to the time-series origin of the data, a continuous autocorrelation structure (corCAR1 in *nlme*-package) was defined by the day of the experiment.

The drivers of ET: The average air temperature during the course of the experiment was 17.5 °C (± 3.1°C – standard deviation). Among the different plots no systematic variation of temperature, relative humidity and solar radiation was measured by the microclimate stations underneath the shelters. Summarizing the different atmospheric components defining rates of ET, ET0 was calculated. During the duration of experiment the average daily ET0 was 3.26 kgH2O m-2 d-1 (± 1.95 SD) with a minimum at 0.75 and a maximum of 6.4 kgH2O m-2 d-1. However, since ET0 is subject to short-term natural variation of the underlying environmental parameters, fluctuations between consecutive days were found to be very pronounced and no temporal trend was revealed over the period of the experiment (Fig. 2).

241

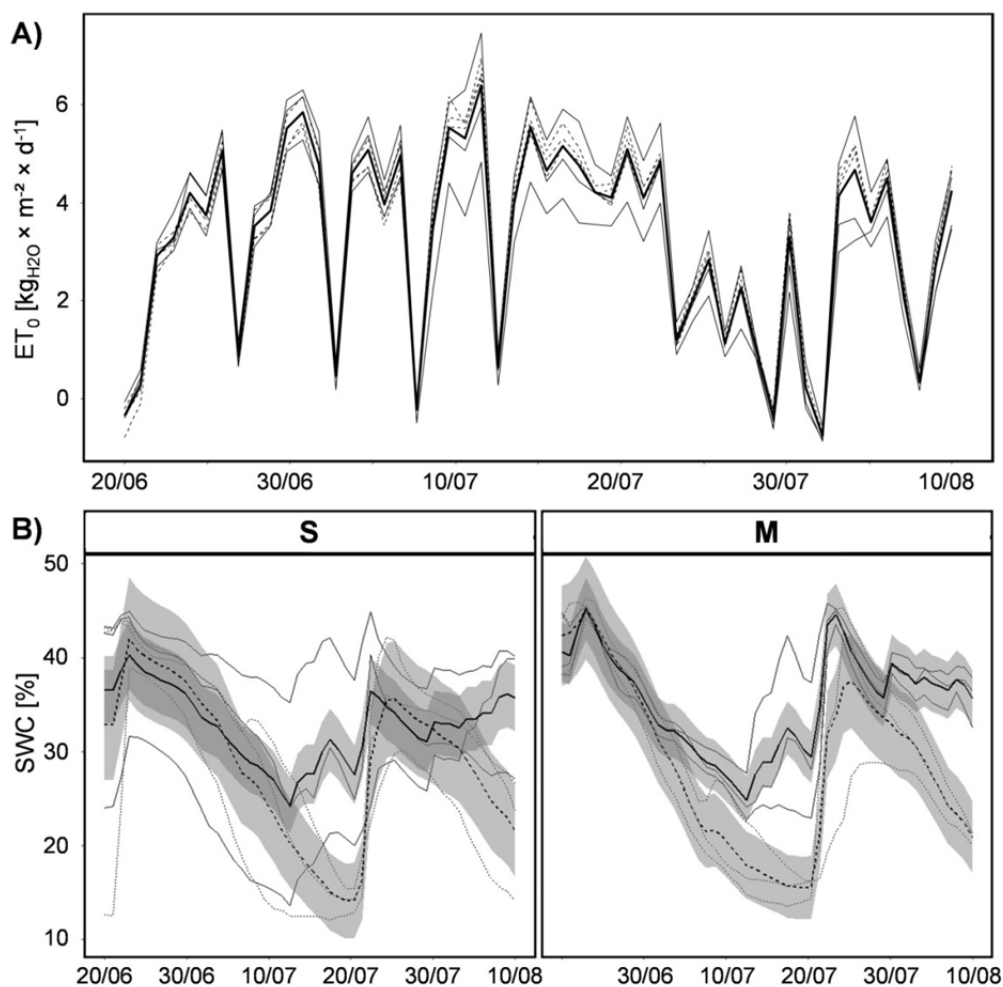



Fig 2: Atmospheric demand (ET0) and soil water content (SWC) as drivers of ET, A) dynamics of daily average ET0 over the course of the experiment (bold line: all plot average, thin lines: individual plots); B) dynamics of daily average SWC for two vegetation types (S & M, see Table 1) in contrasting irrigation schemes (REG - solid lines, D - dashed lines; bold lines: treatment average; shaded area: standard deviation, thin lines: individual plots); S: Stubai, M: Matsch/Mazia.

246

During the time of the experiment the two contrasting irrigation schemes led to distinct SWC dynamics within the respective

mesocosms (Fig. 2). Since SWC in all lysimeters was high at the beginning of the experiment the value initially decreased in

all plots irrespective of treatment indicating that the water irrigated on plots with regular irrigation did not fully compensate

the loss of water by ET of the corresponding communities. The first clear effects of differential irrigation became only

apparent in the lysimeters with the M-type of vegetation after applying approximately two weeks of drought. Variation in

SWC of lysimeters belonging to the S-type of vegetation was rather strong and it took those units longer to manifest distinct

effects of the different watering schemes. After approximately one month, SWC in both vegetation types revealed clear

254 effects of the contrasting irrigation strategies. At that time, SWC of both treatments was restored to similar values observed

255 during the initial stages of the experimental period in order to avoid distress in the drier mesocosms. Rates of daily ET from

256 the lysimeters were varying very strongly through the period of the experiment and did not reveal a general temporal trend

257 (Fig. 3). The average evapotranspirative water loss for the lysimeter unit during the duration of the experiment was 4.9

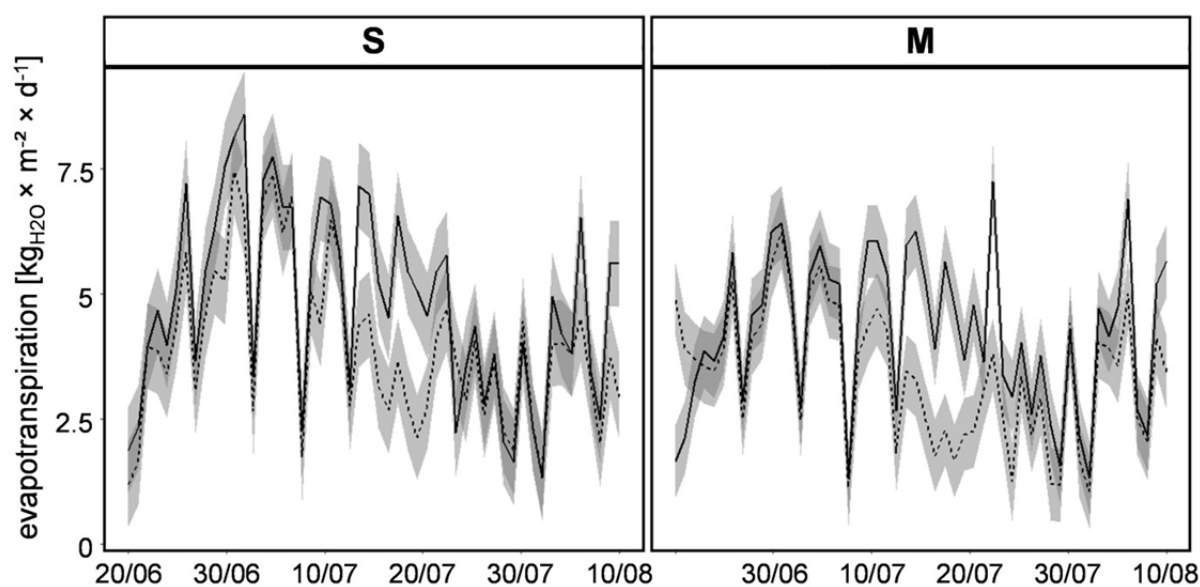
258 kgH20 m-2 d-1. Subject to the atmospheric water vapour pressure deficit the recorded fluxes were characterised by a similar

259 unsteadiness as the variability of the underlying environmental parameters would suggest. No consistent differences in daily

260 water flux from the lysimeter mesocosms to the atmosphere could be detected according to the identity of the community.

261 Also the contrasting irrigation regimes did not impose a overall difference in the rates of ET within the experimental period.

262 However, during periods of strong divergence of SWC among the two irrigation treatments, daily ET was lower for entities

263 subjected to experimental drought.

264
265 **Fig 3: Dynamics of daily average ET over the course of the experiment for two different vegetation types (S & M, Table 1)**
266 **subjected to contrasting irrigation regimes (REG - solid lines, D - dashed lines; shaded area – standard deviation); S: Stubai, M:**
267 **Matsch/Mazia.**

268

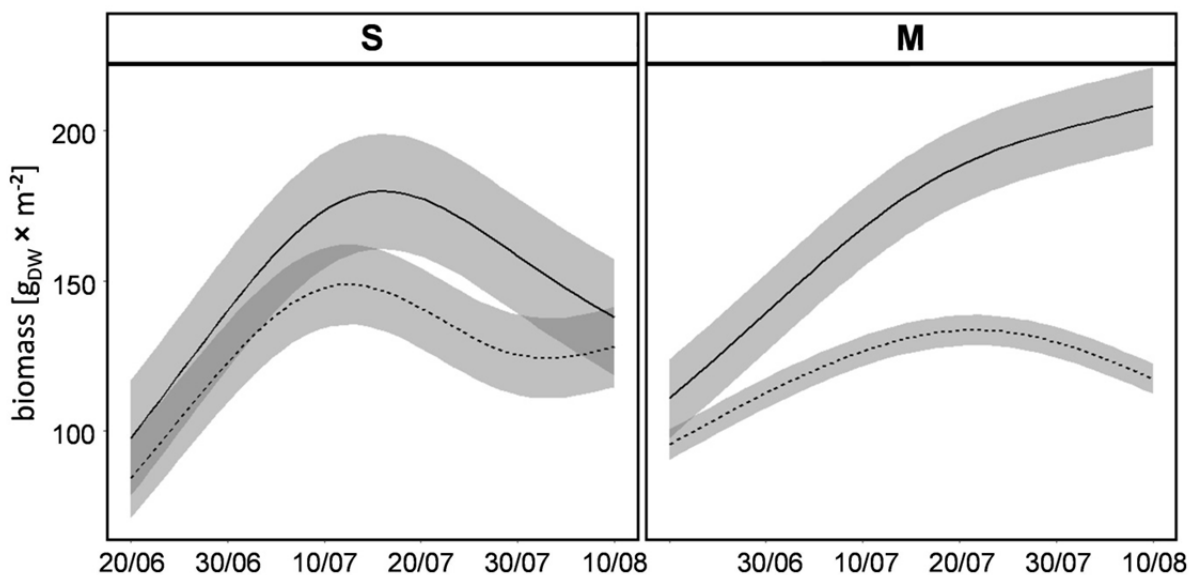



Fig 4: Trajectories of biomass development for the two vegetation types (S: Stubai, M: Matsch/Mazia, Table 1) subjected to contrasting irrigation regimes (REG - solid lines, D - dashed lines; shaded area – standard deviation) throughout the duration of the experiment

The prediction of biomass development combined from the different non-invasive estimation methods suggested distinct growth trajectories for the two vegetation types in interaction with the two irrigation regimes. The mesocosms with communities belonging to the local S-type revealed larger biomass differentials during early stages of the experiment irrespective of the applied irrigation regime. However, with increasing duration of the experiment, growth dynamics started diverging in treatments with contrasting water provision, with biomass differences peaking at the mid-time of the experimental period. After that peak, the prediction of dry weight suggested a decline in standing biomass for both water regimes in the S-communities. Towards the end of the experiment, biomasses of communities in the different water treatments converged to similar values. A different pattern of biomass development was detected for the transplanted mesocosms (M). From the beginning of the experiment growth processes of the different irrigation treatments yielded distinct trajectories. In the treatment experiencing regular water provision the biomass gain per unit time was stronger than in the mesocosms being subjected to irregular watering. That pattern was consistent throughout the experiment, with a strictly monotonic increase of standing biomass in the M communities of well-watered plots. In contrast, the vegetation of the M-type in the plots with restricted watering growth started stagnating during the second half of the experimental period. Unlike the S-type, at the end of the investigation period, biomasses in the M-type communities were clearly distinct according to the different watering regimes, with the standing mass in the regularly watered plots approximating double the amount compared to the treatment with restricted water provision.

290

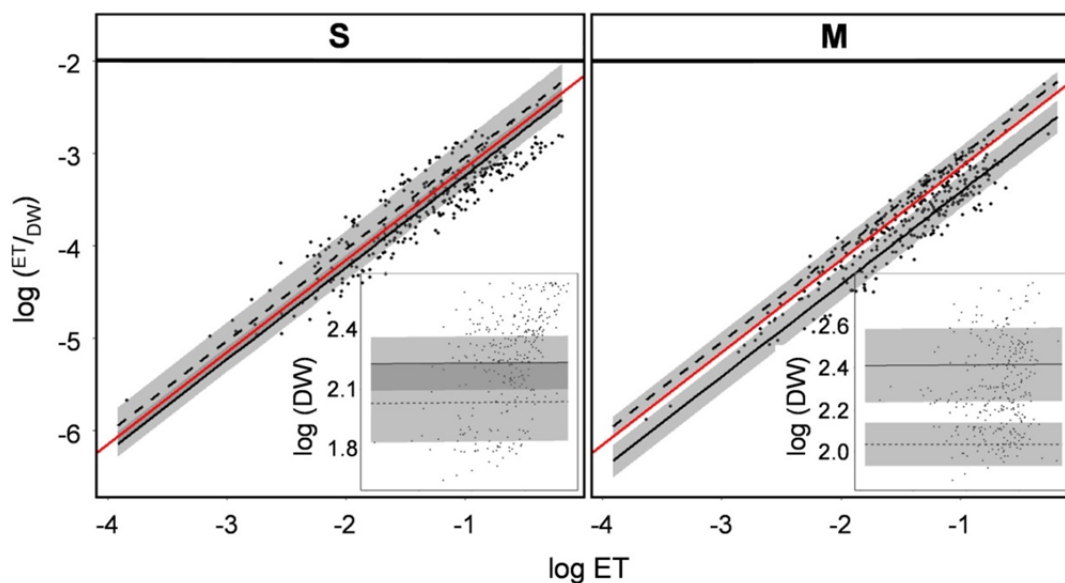



Fig 5: Log-log scaling for the two factors defining variability of ET: ET rates per unit dry weight (ET/DW) and standing biomass (=dry weight, DW) for the two different vegetation types (S & M, Table 1) subjected to contrasting irrigation regimes (REG - solid lines, D - dashed lines; shaded area – standard deviation), red line indicates a reference function with the slope of 1.

294

Variability of ET is subject to variation in evapotranspiration rates per unit biomass (ET/DW) and the variation in the standing biomass. Hence, when comparing rates of ET differentiating both underlying components will provide deeper insights on how the vegetation interface of different communities mediates the water flux from the soil. A strong positive correlation of total daily ET and ET/DW was found (Fig 5). The log-log-scaling of ET/DW with ET revealed a slope of 0.998 arguing that variation in ET rates measured during the course of this experiment is almost exclusively defined by the variation in ET rates per unit biomass (100% = 1). This relationship was independent of vegetation type and irrigation scheme. The effect of biomass variation on the variance of total rates of ET however did have a very small and insignificant effect. For the local communities (S) the more biomass to be found in the lysimeter mesocosms the bigger was the total daily water flux to the atmosphere, while the transplanted communities revealed a different pattern. For M-type communities the amount of biomass in the lysimeters had no strong effect on the rates of total ET.

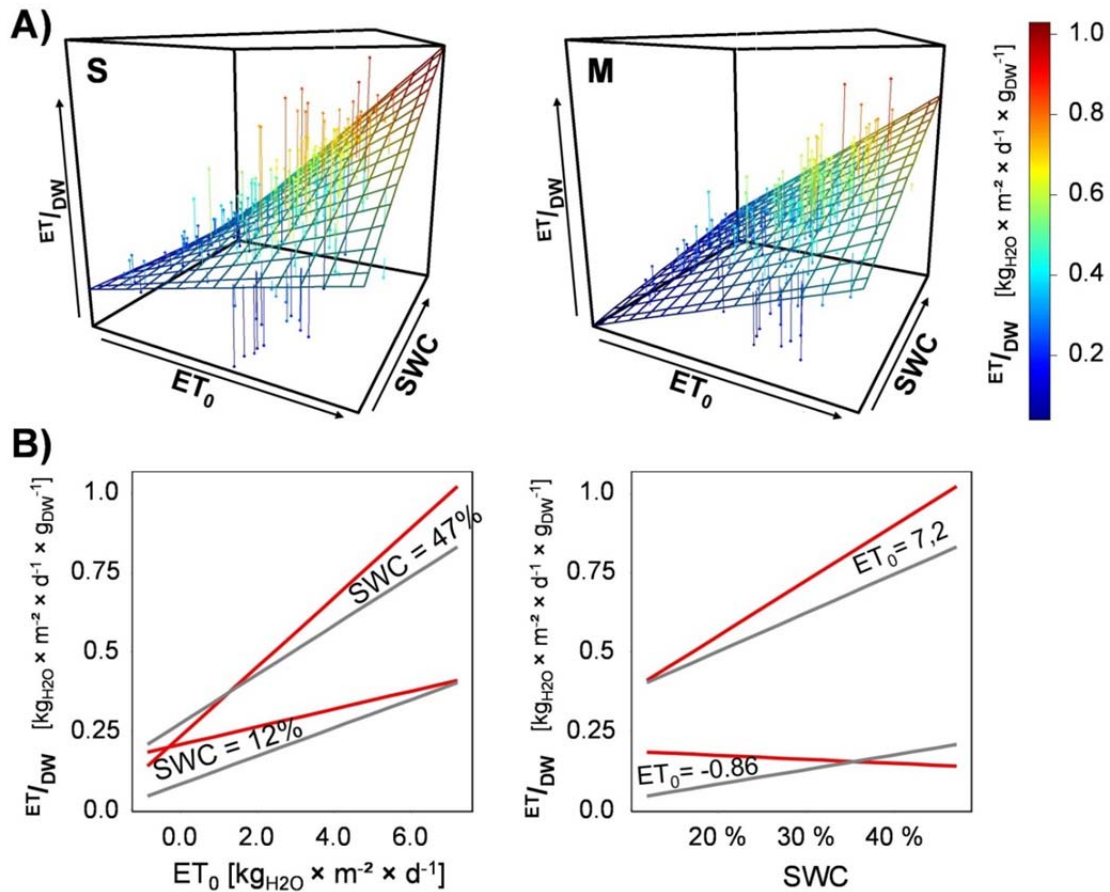



Fig 6 A) 3D plots: response surface of ET per unit DW (ET/DW) along the two-dimensional variation of ET0 and SWC for the two different vegetation types (S: Stubai, M: Matsch/Mazia, Table 1); B) projections of ET/DW response along ET0 and SWC at maximum/minimum value of the particular other (red: S-communities, grey: M-communities)

After revealing ET/DW as the most important driver in defining variation in the rates of total ET from the lysimeter mesocosms, the effect of combined variation in ET_0 and SWC on rates of ET per unit biomass was modelled in dependence of the vegetation type (ET/DW = f(ET_0×SWC×vegetation type)). The average daily sums of ET_0 ranged from -0.75 to a maximum of 6.4 kg_{H2O} m^{-2} d^{-1}, while the averaged SWC realized during the duration of the experiment covered a range from approximately 12-47% (Fig. 5). Both, ET_0 and SWC had a highly significant and positive effect on achieved rates of ET/DW (Fig. 6, Table 2). However, as implied by a significant synergistic interaction of ET_0 and SWC, rates of ET/DW increased stronger if SWC and ET_0 increased concurrently than the individual gradients of either would imply (Fig 6.). With increasing ET_0 the response of EVT/DW was stronger the higher SWC was. However, there was a significant difference how both vegetation types responded within the landscape of environmental drivers defining ET/DW (Table 2). The local (S) vegetation had higher rates of ET/DW - when both ET_0 and SWC were low - than the transplanted vegetation type (M), suggesting a higher base rate of ET/DW. On the low end of investigated SWC the M-vegetation had a stronger response to

320 ET_0 than the local S-vegetation. Despite that stronger response of the transplanted vegetation (M) along the ET_0 gradient at

321 low SWC, the maximum rates of ET/DW converted to similar values due to the higher base flux at low ET_0/ low SWC in the

322 S-vegetation. In turn, under conditions of high soil water availability the ET_0-response of the S-type was much more

323 pronounced than in the M-type. A similar pattern was found comparing the SWC-response of both vegetation types for the

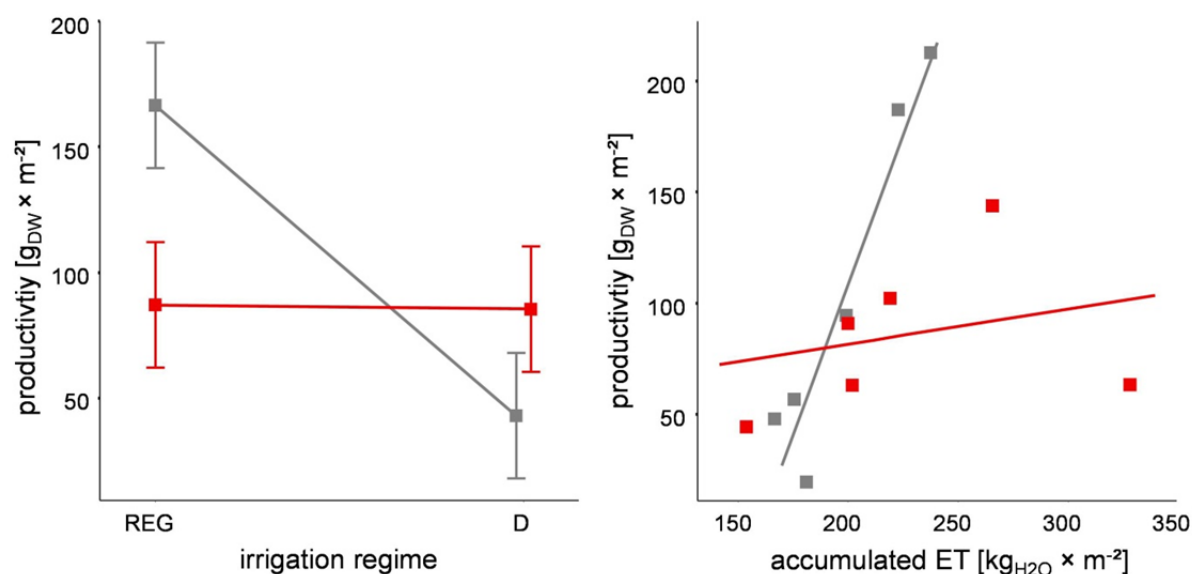
324 range of different ET_0 values realized during the experiment. At low ET_0 the M-type vegetation responded stronger to

325 variations in SWC, while there was almost no response in the S-type. However, at high ET_0 the response of the S-type to

326 increasing SWC was again much more pronounced than in lysimeters with the M-type. Because of the higher rates of

327 ET/DW at low ET_0/SWC and the overall increased response potential of the S-type vegetation, the ET/DW values achieved

328 in the M-communities stayed below those found in the local vegetation for almost the entire range of combinations between

329 ET_0 and SWC investigated in this experiment.

330

331 **Fig 7: Productivity of two vegetation types (± standard error, Stubai - red & Matsch/Mazia - grey; Table 1) subjected to**
332 **contrasting irrigation schemes (Fig 1), right panel: dry matter productivity of two vegetation types (see above) as function of**
333 **accumulated evapotranspiration over the experimental duration**

334 Comparing the productivity of the two vegetation types among the two irrigation treatments revealed a contrasting

335 response for the DW productivity (Fig. 7, left panel). For the local S-Type the biomass gain over the experimental period did

336 not show a strong dependence on the applied watering regime. The productivity of the S-type stayed well below from what

337 would be expected for the vegetation outside the experimental site in both treatments. For the M-communities, however,

338 productivity was on average more than two fold higher in the plots experiencing regular water provision compared to those

339 exposed to extended periods of drought.

340 Integrated over the entire experimental period, the biomass productivity per unit water was significantly higher for the

341 transplanted mesocosms M (Fig 7, right panel). The data suggested a productivity increase of 2.6g_{DW} per kg of water for the

342 M vegetation. In contrast, for the S-type mesocosms the average increase of productivity per 1kg of evapotranspiration was

343 approximately only 0.16g. This pattern suggests that biomass generation in the M-type vegetation is significantly more

344 dependent on water availability, while the differences in the slope imply lower efficiency of water use with respect to dry

345 weight accumulation in the S mesocosms.

346

347   It is intuitive to understand, that ET_0 and SWC impose independent and interacting effects on water fluxes from the

348 soil to the atmosphere with one of either constraining the total rates of ecosystem ET (Kim and Verma, 1991; Perez et al.,

349 2006). Beyond the effects of these abiotic drivers, the measurements of the present experiment reveal a community specific

350 signal in the definition of ecosystem water exchange. The community specific configuration of the soil-plant-atmosphere

351 interface is instinctively acknowledged if distinct vegetation types are compared. Water fluxes from the system will to some

352 degree always scale with productivity and total biomass of the vegetation (Zeppel et al., 2014and references therein). This

353 context will drive variation in ET of contrasting biomes together with environmental parameters affecting the availability of

354 water and the atmospheric deficit.

355   However, results of this experiment reveal that vegetation specific differences have a component, which defines

356 ecosystem water flux beyond the impact of variations in total biomass. Such differences will be important to understand and

357 to consider if communities of the same type need to be evaluated with respect to their particular impact on the hydrological

358 regulation of the ecosystem. The response of water fluxes along co-operating gradients of SWC and ET_0 indicated

359 divergence in the conductance potential of the two alpine grassland communities, which were independent from the biomass

360 present. At low SWC the response of the M-type to increasing ET_0 was much stronger than for the S-type arguing for a

361 higher efficiency to mobilise limited water resources from the soil column. Conversely, under conditions of high soil water

362 availability water fluxes from the S-type responded much stronger to increases of ET_0 suggesting a higher overall

363 conductance potential. Similar implications were revealed along the gradient of soil water availability. SWC variations had

364 almost no effect on the S-type communities when the atmospheric draw was small, while the M-type mesocosm still

365 mediated fluxes to the atmosphere. Under high ET_0 however, the divergence in the response of ET between S & M-

366 communities to varying SWC suggests that, from starting at similar rates, the S-type became much more efficient to conduct

367 water to the atmosphere the less soil water became limiting. These differences between the two vegetation types indicate

368 different strategies in the water utilisation. For the M-type this strategy may be summarized by a high potential to utilize

369 even scarce water resources, a lower potential to translate atmospheric deficits into higher water conductance with rates of

370 ET staying below those measured for the S-type for most environmental scenarios included within the experimental period.

371 This implies an overall conservative and water saving strategy. For the S-communities, in contrast, which show high water

372 conductance potential with strongly increasing ET rates when environmental conditions become less constraining, an

373 acquisitive strategy is suggested. With high rates even at base level these communities appear not to be optimized to save

374 water and might experience drought effects earlier and probably stronger, when water availability becomes limiting. There
375 might be some dampening effect as soil hydrological properties indicate a higher amount of plant available water for the S-
376 type. The permanent wilting point (pF 4.2) in the main rooting zone (averaged values for 0.05m, 0.15m, 0.25m soil depth)
377 was at a SWC of 13% (± 8.3 SD) and 17% (± 3.1 SD) for the S-vegetation type and the M-vegetation type, respectively.
378 Whereas field capacity (pF 2.1) was found to be at a SWC of 46% (± 4.4 SD) and 43% (± 6.8%) for the S-vegetation type
379 and the M-vegetation type, respectively. In summary, the plant available water was found to be 33 vol% for the S-type and
380 26 vol% for the M-type. However, the variation at 0.05m soil depth was very low and even a slightly higher amount of plant
381 available water was found for the M-type (S-type: 28 vol%; M-type: 29 vol%) at this soil depth. Although soil hydrological
382 properties play a role in the community specific conductance potential of soil water to the atmosphere, differences found for
383 the investigated two different vegetation types turned out to be not decisive in this context.

384   Sharing a common environment, the differences in biomass-independent conductance potential between the two
385 Alpine grassland communities are likely to have a foundation in a contrasting physiological, functional and structural
386 organisation of the vegetation. Functional divergence in water utilisation, evapotranspiration and other aspects of
387 hydrological regulation of ecosystems (e.g. infiltration, surface run-off) between communities can be manifested by the
388 frequency distribution in the values of particular traits (Díaz et al., 2013). Canopy complexity - density and size, growth
389 form composition, composition and diversity of vascular structures, stomatal density and conductance mediate community
390 specific differences in the evapotranspiration aboveground (de Bello et al., 2010) Belowground, the structure and depth of
391 the individual rooting systems is an important determinant for the water utilisation potential of communities (Knapp et al.,
392 2008). Along the variation and composition of these traits water usage and consequently also drought resistance of
393 contrasting communities is defined. The differences in the two vegetation types suggest high exploitation potential for scarce
394 soil water, probably facilitated by a higher priority on water exploitation in the soil in the M-mesocosms and, conversely, a
395 stronger importance on aboveground structures mediating light capture and gas-exchange, leading to an increased response
396 potential of ET for atmospheric triggers in the local S-communities.

397   The clear vegetation response to variable water availability observed in the present experiment is not common in
398 studies targeting Alpine grasslands (de Bello et al., 2010). Based on multi-annual measurements of evapotranspiration at 16
399 sites in the Austrian Alps, it was suggested, that even during years with low annual precipitation Alpine grasslands do not
400 experience water stress (Wieser et al., 2008). Gilgen and Buchmann (2009) could not conclude on a general drought
401 response of grasslands in Switzerland, while acknowledging a site-specific impact with communities receiving less annual
402 precipitation being more susceptible to drought stress than those at higher rainfall levels. Also arguing for a co-defined and
403 interactive manifestation in the effects of varying water availability, a strong drought response of Alpine grassland
404 functioning was revealed under scenarios of co-occurring heat waves (De Boeck et al., 2016). A modelling study for
405 grassland ecosystems in the Austrian- and French Alps suggested a higher vulnerability to drought for communities with a
406 water spending strategy targeting on water provision of the ecosystems in general (Leitinger et al., 2015). However, it seems
407 inappropriate to synthesize a general summary on the response of Alpine grasslands to variations in water availability given

408 the small body of research performed. Considering the different spatio-temporal scales, the range of parameters measured,

409 and the management and biodiversity spectrum of different grassland types in the Alps, drawing broad and universal

410 generalisation yet becomes unrewarding. For experiments with contrasting treatments the practicalities of manipulating

411 water availability potentially also need to be considered for the interpretation of the results.

412   Drought scenarios are usually generated by rain-out shelters using a UV-permeable, transparent film for roofing. If

413 compared to unroofed controls, temperature differences and attenuation of photosynthetically active radiation reducing total

414 productivity will have to be expected as pure artefacts of the sheltering (Vogel et al., 2013). However, even if both

415 treatments are sheltered, differential irrigation may not immediately lead to the realisation of varying water availabilities.

416 The beginning of the present experiment was marked by the establishment of the rain-out shelters and the omission of

417 irrigation in the treatments with irregular watering (D). From this point, it took approximately two weeks for the SWC of

418 both irrigation schemes to diverge significantly in M-type mesocosms, for the S-type even longer. Therefore, regular

419 irrigation and, respectively, its omission can, counter-intuitively, only be an indicator of contrasting water availability. The

420 establishment of drought conditions in the strict sense of a depleted soil water reservoir is realized by the interaction of pre-

421 treatment SWC, standing biomass and atmospheric effects. Variations in vegetation water status have to be defined in

422 context of water availability (supply) and physiology, phenology and the leaf-to-air evaporative gradient (Gilbert and

423 Medina, 2016). The beginning of the experiment was characterized by combination of days with consistently high averages

424 of ET_0 and high SWC in all mesocosms. This combination led to high ET and a decrease of SWC for all experimental units.

425 Due to the parallel decline of SWC irrespective the watering regime applied, the water availability differentiation among the

426 treatments was delayed. For such reasons, it was argued to define variations in water availability not purely on the basis of

427 contrasting regimes of water input (i.e. irrigated vs. non-irrigated) if these are not causing systematic variations in soil

428 moisture (Kramer, 1983). Defining water supply based on the continuous range of SWC rather than discrete irrigation

429 treatments considers soil type specific characteristics of matric potential and hydraulic conductivity. Also practical problems

430 with realizing discrete treatments of water availability in the field (i.e. precipitation entry to sheltered plots due to heavy

431 winds, spatio-temporal variation in the effectiveness of automated irrigation) will be migrated by referencing ecosystem

432 responses to gradients of water supply. Defining vegetation responses along continuous ranges of environmental factors will

433 further yield stronger information about the response surface of the system and improves model building and testing (Beier

434 et al., 2012).

435   Irrespective the variability of different water availabilities within the two irrigation regimes, mesocosms subjected to

436 regular watering (REG) had on average a higher productivity than those with irregular and in total less irrigation. However,

437 significant differences between the different communities were found in the response to variations in the water supply (Fig

438 7). Relating total productivity to the amount of evapotranspirative water release over the experimental period revealed a

439 higher biomass gain per unit water in the M-type communities. The higher water use efficiency in the biomass production of

440 these mesocosms together with their overall stronger water saving strategy reinforces their optimisation to scarce water

441 supply. For the local S-communities, in contrast, the low biomass differential per unit water consumption indicates a high

442 potential to conduct water from the soil to the atmosphere and that productivity of this vegetation is probably not often
443 constrained by water availability in its natural context. (Brilli et al., 2011) expect from a water spending strategy to have a
444 cooling feedback in terms of climate warming. However, a negative feedback for water provision services (i.e. down-stream
445 water users) has to be expected. Further decisive changes remain debatable: How will 'water spending' plant communities
446 adapt if droughts occur more frequently and possibly with higher intensities (Bahn et al., 2014; Reichstein et al., 2013). To
447 what extent play – at least initially - physiological and morphological changes a role or is there an immediate shift to a better
448 adapted community?

449

450 We wish to thank Valentin Schießendoppler, Jana Schönherr and Jakob Fitzner for their help in the field and during
451 the analysis in the lab. The funding partners that have supported this research include the project ClimAgro (Autonome
452 Provinz Bozen – Südtirol, Abteilung Bildungsförderung, Universität und Forschung) and the Austrian Federal Ministry of
453 Science, Research and Economy with the HRSM – cooperation project KLIMAGRO. This study was conducted on the
454 LTER site 'Stubai Valley' (LTSER platform 'Tyrolean Alps') and the LTSER platform 'Val Mazia/Matschertal'). Both sites
455 belong to the national and international Long-Term Ecological Research Networks (LTER-Austria, LTER-Italy, LTER-
456 Europe and ILTER). UT and GL are part of the research focus 'Alpine Space – Man and Environment' at the University of
457 Innsbruck.

458

459 **References**

460 Allen, R. G., Pereira, L. S., Raes, D., and Smith, M.: Crop evapotranspiration - Guidelines for computing crop water
461 requirements - FAO Irrigation and drainage paper 56, FAO, Rome, Italy, 1998.

462 Auer, I., Böhm, R., Jurkovic, A., Lipa, W., Orlik, A., Potzmann, R., Schöner, W., Ungersböck, M., Matulla, C., Briffa, K.,
463 Jones, P., Efthymiadis, D., Brunetti, M., Nanni, T., Maugeri, M., Mercalli, L., Mestre, O., Moisselin, J.-M., Begert,
464 M., Müller-Westermeier, G., Kveton, V., Bochnicek, O., Stastny, P., Lapin, M., Szalai, S., Szentimrey, T., Cegnar, T.,
465 Dolinar, M., Gajic-Capka, M., Zaninovic, K., Majstorovic, Z., and Nieplova, E.: HISTALP—historical instrumental
466 climatological surface time series of the Greater Alpine Region, International Journal of Climatology, 27, 17-46,
467 2007.

468 Bahn, M., Reichstein, M., Dukes, J. S., Smith, M. D., and McDowell, N. G.: Climate–biosphere interactions in a more
469 extreme world, New Phytologist, 202, 356-359, 2014.

470   Beier, C., Beierkuhnlein, C., Wohlgemuth, T., Penuelas, J., Emmett, B., Körner, C., de Boeck, H., Christensen, J. H.,
471   Leuzinger, S., Janssens, I. A., and Hansen, K.: Precipitation manipulation experiments – challenges and
472   recommendations for the future, Ecology Letters, 15, 899-911, 2012.

473   Beniston, M.: Impacts of climatic change on water and associated economic activities in the Swiss Alps, Journal of
474   Hydrology, 412, 291-296, 2012.

475   Beniston, M.: Mountain Climates and Climatic Change: An Overview of Processes Focusing on the European Alps, pure and
476   applied geophysics, 162, 1587-1606, 2005.

477   Beniston, M., Stephenson, D. B., Christensen, O. B., Ferro, C. A. T., Frei, C., Goyette, S., Halsnaes, K., Holt, T., Jylhä, K.,
478   Koffi, B., Palutikof, J., Schöll, R., Semmler, T., and Woth, K.: Future extreme events in European climate: an
479   exploration of regional climate model projections, Climatic Change, 81, 71-95, 2007.

480   Bogena, H., Schulz, K., and Vereecken, H.: Towards a network of observatories in terrestrial environmental research, Adv.
481   Geosci., 9, 109-114, 2006.

482   Böhm, R., Auer, I., Brunetti, M., Maugeri, M., Nanni, T., and Schöner, W.: Regional temperature variability in the European
483   Alps: 1760–1998 from homogenized instrumental time series, International Journal of Climatology, 21, 1779-1801,
484   2001.

485   Brilli, F., Hörtnagl, L., Hammerle, A., Haslwanter, A., Hansel, A., Loreto, F., and Wohlfahrt, G.: Leaf and ecosystem
486   response to soil water availability in mountain grasslands, Agricultural and Forest Meteorology, 151, 1731-1740,
487   2011.

488   Ciccarelli, N., von Hardenberg, J., Provenzale, A., Ronchi, C., Vargiu, A., and Pelosini, R.: Climate variability in north-
489   western Italy during the second half of the 20th century, Global and Planetary Change, 63, 185-195, 2008.

490   de Bello, F., Lavorel, S., Díaz, S., Harrington, R., Cornelissen, J. H. C., Bardgett, R. D., Berg, M. P., Cipriotti, P., Feld, C.
491   K., Hering, D., Martins da Silva, P., Potts, S. G., Sandin, L., Sousa, J. P., Storkey, J., Wardle, D. A., and Harrison, P.
492   A.: Towards an assessment of multiple ecosystem processes and services via functional traits, Biodiversity and
493   Conservation, 19, 2873-2893, 2010.

494   De Boeck, H. J., Bassin, S., Verlinden, M., Zeiter, M., and Hiltbrunner, E.: Simulated heat waves affected alpine grassland
495   only in combination with drought, New Phytologist, 209, 531-541, 2016.

496   Díaz, S., Purvis, A., Cornelissen, J. H. C., Mace, G. M., Donoghue, M. J., Ewers, R. M., Jordano, P., and Pearse, W. D.:
497   Functional traits, the phylogeny of function, and ecosystem service vulnerability, Ecology and Evolution, 3, 2958-
498   2975, 2013.

499   Estiarte, M., Vicca, S., Peñuelas, J., Bahn, M., Beier, C., Emmett, B. A., Fay, P. A., Hanson, P. J., Hasibeder, R., Kigel, J.,
500   Kröel-Dulay, G., Larsen, K. S., Lellei-Kovács, E., Limousin, J.-M., Ogaya, R., Ourcival, J.-M., Reinsch, S., Sala, O.
501   E., Schmidt, I. K., Sternberg, M., Tielbörger, K., Tietema, A., and Janssens, I. A.: Few multiyear precipitation–
502   reduction experiments find a shift in the productivity–precipitation relationship, Global Change Biology, 22, 2570-
503   2581, 2016.

504   Gilbert, M. E. and Medina, V.: Drought Adaptation Mechanisms Should Guide Experimental Design, Trends in Plant
505   Science, 21, 639-647, 2016.

506   Gilgen, A. K. and Buchmann, N.: Response of temperate grasslands at different altitudes to simulated summer drought
507   differed but scaled with annual precipitation, Biogeosciences, 6, 2525-2539, 2009.

508   Gobiet, A., Kotlarski, S., Beniston, M., Heinrich, G., Rajczak, J., and Stoffel, M.: 21st century climate change in the
509   European Alps—A review, Science of The Total Environment, 493, 1138-1151, 2014.

510   Heimann, M. and Reichstein, M.: Terrestrial ecosystem carbon dynamics and climate feedbacks, Nature, 451, 289-292,
511   2008.

512   IPCC: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report
513   of the Intergovernmental Panel on Climate Change, Cambridge, United Kingdom and New York, NY, USA, 1535
514   pp., 2013.

515   IPCC: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of
516   Working Groups I and II of the Intergovernmental Panel on Climate Change, Cambridge University Press,
517   Cambridge, UK and New York, NY, USA, 2012.

518   Jasechko, S., Sharp, Z. D., Gibson, J. J., Birks, S. J., Yi, Y., and Fawcett, P. J.: Terrestrial water fluxes dominated by
519   transpiration, Nature, 496, 347-350, 2013.

520   Jonasson, S.: Evaluation of the Point Intercept Method for the Estimation of Plant Biomass, Oikos, 52, 101-106, 1988.

521   Kim, J. and Verma, S. B.: Modeling canopy stomatal conductance in a temperate grassland ecosystem, Agricultural and
522   Forest Meteorology, 55, 149-166, 1991.

523   Knapp, A. K., Beier, C., Briske, D. D., Classen, A. T., Luo, Y., Reichstein, M., Smith, M. D., Smith, S. D., Bell, J. E., Fay,
524   P. A., Heisler, J. L., Leavitt, S. W., Sherry, R., Smith, B., and Weng, E.: Consequences of More Extreme Precipitation
525   Regimes for Terrestrial Ecosystems, BioScience, 58, 811-821, 2008.

526   Kramer, P. J.: Water Relations of Plants, Academic Press, 1983.

527   Lati, R. N., Manevich, A., and Filin, S.: Three-dimensional image-based modelling of linear features for plant biomass
528   estimation, International Journal of Remote Sensing, 34, 6135-6151, 2013.

529   Leitinger, G., Ruggenthaler, R., Hammerle, A., Lavorel, S., Schirpke, U., Clement, J.-C., Lamarque, P., Obojes, N., and
530   Tappeiner, U.: Impact of droughts on water provision in managed alpine grasslands in two climatically different
531   regions of the Alps, Ecohydrology, 8, 1600-1613, 2015.

532   Machado, S., Bynum, E. D., Archer, T. L., Lascano, R. J., Wilson, L. T., Bordovsky, J., Segarra, E., Bronson, K., Nesmith,
533   D. M., and Xu, W.: Spatial and Temporal Variability of Corn Growth and Grain Yield This research was supported
534   by the Texas State Legislature Initiative on Precision Agriculture for the Texas High Plains, Crop Science, 42, 1564-
535   1576, 2002.

536   Messerli, B., Viviroli, D., and Weingartner, R.: Mountains of the world: Vulnerable Water Towers for the 21(st) century,
537   Ambio, 2004. 29-34, 2004.

538   Newesely, C., Leitinger, G., Zimmerhofer, W., Kohl, B., Markart, G., Tasser, E., and Tappeiner, U.: Rain simulation in
539   patchy landscapes: Insights from a case study in the Central Alps, CATENA, 127, 1-8, 2015.

540   Peñuelas, J., Gordon, C., Llorens, L., Nielsen, T., Tietema, A., Beier, C., Bruna, P., Emmett, B., Estiarte, M., and Gorissen,
541   A.: Nonintrusive Field Experiments Show Different Plant Responses to Warming and Drought Among Sites, Seasons,
542   and Species in a North–South European Gradient, Ecosystems, 7, 598-612, 2004.

543   Perez, P. J., Lecina, S., Castellvi, F., Martínez-Cob, A., and Villalobos, F. J.: A simple parameterization of bulk canopy
544   resistance from climatic variables for estimating hourly evapotranspiration, Hydrological Processes, 20, 515-532,
545   2006.

546   Peters, A., Nehls, T., Schonsky, H., and Wessolek, G.: Separating precipitation and evapotranspiration from noise – a
547   new filter routine for high-resolution lysimeter data, Hydrol. Earth Syst. Sci., 18, 1189-1198, 2014.

548   R Development Core Team: R: A language and environment for statistical computing. R Foundation for Statistical
549   Computing, Vienna, Austria, 2015.

550 Rebetez, M. and Reinhard, M.: Monthly air temperature trends in Switzerland 1901–2000 and 1975–2004, Theoretical and
551   Applied Climatology, 91, 27-34, 2008.

552 Reichstein, M., Bahn, M., Ciais, P., Frank, D., Mahecha, M. D., Seneviratne, S. I., Zscheischler, J., Beer, C., Buchmann, N.,
553   Frank, D. C., Papale, D., Rammig, A., Smith, P., Thonicke, K., van der Velde, M., Vicca, S., Walz, A., and
554   Wattenbach, M.: Climate extremes and the carbon cycle, Nature, 500, 287-295, 2013.

555 Renton, M. and Poorter, H.: Using log–log scaling slope analysis for determining the contributions to variability in
556   biological variables such as leaf mass per area: why it works, when it works and how it can be extended, New
557   Phytologist, 190, 5-8, 2011.

558 Schindler, U.: A rapid method for measuring the hydraulic conductivity in cylinder core samples from unsaturated soil,
559   Archiv fur Acker- und Pflanzenbau und Bodenkunde, 24, 1-7, 1980.

560 Schrader, F., Durner, W., Fank, J., Gebler, S., Pütz, T., Hannes, M., and Wollschläger, U.: Estimating Precipitation and
561   Actual Evapotranspiration from Precision Lysimeter Measurements, Procedia Environmental Sciences, 19, 543-552,
562   2013.

563 Silva, L. C. R.: From air to land: understanding water resources through plant-based multidisciplinary research, Trends in
564   Plant Science, 20, 399-401, 2015.

565 Solomon, S., Plattner, G.-K., Knutti, R., and Friedlingstein, P.: Irreversible climate change due to carbon dioxide emissions,
566   Proceedings of the National Academy of Sciences, 106, 1704-1709, 2009.

567 Tackenberg, O.: A New Method for Non-destructive Measurement of Biomass, Growth Rates, Vertical Biomass Distribution
568   and Dry Matter Content Based on Digital Image AnalysisTackenberg — Image Analysis for Non-destructive Biomass
569   MeasurementTackenberg — Image Analysis for Non-destructive Biomass Measurement, Annals of Botany, 99, 777-
570   783, 2007.

571 van der Schrier, G., Efthymiadis, D., Briffa, K. R., and Jones, P. D.: European Alpine moisture variability for 1800–2003,
572   International Journal of Climatology, 27, 415-427, 2007.

573 Viviroli, D., Weingartner, R., and Messerli, B.: Assessing the Hydrological Significance of the World's Mountains,
574   Mountain Research and Development, 23, 32-40, 2003.

575   Vogel, A., Fester, T., Eisenhauer, N., Scherer-Lorenzen, M., Schmid, B., Weisser, W. W., and Weigelt, A.: Separating
576   Drought Effects from Roof Artifacts on Ecosystem Processes in a Grassland Drought Experiment, PLOS ONE, 8,
577   e70997, 2013.

578   Wieser, G., Hammerle, A., and Wohlfahrt, G.: The Water Balance of Grassland Ecosystems in the Austrian Alps, Arctic,
579   Antarctic, and Alpine Research, 40, 439-445, 2008.

580   Wohlfahrt, G., Hammerle, A., Haslwanter, A., Bahn, M., Tappeiner, U., and Cernusca, A.: Seasonal and inter-annual
581   variability of the net ecosystem CO_2 exchange of a temperate mountain grassland: Effects of weather and
582   management, Journal of Geophysical Research: Atmospheres, 113, n/a-n/a, 2008.

583   Zacharias, S., Bogena, H., Samaniego, L., Mauder, M., Fuß, R., Pütz, T., Frenzel, M., Schwank, M., Baessler, C.,
584   Butterbach-Bahl, K., Bens, O., Borg, E., Brauer, A., Dietrich, P., Hajnsek, I., Helle, G., Kiese, R., Kunstmann, H.,
585   Klotz, S., Munch, J. C., Papen, H., Priesack, E., Schmid, H. P., Steinbrecher, R., Rosenbaum, U., Teutsch, G., and
586   Vereecken, H.: A Network of Terrestrial Environmental Observatories in Germany, Vadose Zone Journal, 10, 955-
587   973, 2011.

588   Zeppel, M. J. B., Wilks, J. V., and Lewis, J. D.: Impacts of extreme precipitation and seasonal changes in precipitation on
589   plants, Biogeosciences, 11, 3083-3093, 2014.