Response of water fluxes and biomass production~~balance components~~ to climate change in permanent grassland soil ecosystems

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Abstract

~~Climate alter water fluxes and aboveground biomass production (AGB) of grasslands. Hydrological processes are affected by changing climatic conditions. In grassland areas, changes in the ecosystem water balance components will alter aboveground biomass production (AGB), which in turn is of great importance for ecological and economic benefits of grassland. However, T~~~~the e~~Effects of climate change on the ecosystem productivity and water fluxes ~~are often~~have been ~~derived from~~studied in ~~specific~~various types of- ~~climate change~~ experiment~~s~~. However, ~~I~~it is still largely unknown whether and how the experimental approach itself affects the results of such studies. ~~Therefore~~We ~~used~~employed ~~t~~~~The aim of this investigation was to identify the effects of climate change on the water balance and the productivity of grassland ecosystems by comparing results of~~ two contrasting experimental approaches using high precision weighable monolithically lysimeters over a period of four years ~~of climate change experiments~~ to identify and compare the responses of water fluxes and aboveground biomass -to climate change in permanent grassland~~s by the use of high precision weighable monolithically lysimeter over a period of four years~~. The first, manipulative approach is based on controlled ~~(manipulative) climate change approach uses increased~~ increases ~~important factors (~~of atmospheric CO_2 concentration~~s~~ and surface temperature~~s),~~. T~~ while~~ . ~~t~~he second~~, (observational)~~ observational approach ~~(observational)~~ uses data from a space-for-time substitution ~~approach~~ along a gradient of~~in~~ climatic conditions.~~ The climate change effects on the ecosystem’s water balance was determined by using high-precision weighable monolithically lysimeters at each site over a period of four years., including the exceptionally dry year 2018.~~ The Budyko framework ~~aridity index, defined as the grass-reference evapotranspiration (ET_0) to precipitation (P)~~ was used to identify if the ~~characterize the hydrological status of~~ ~~each~~ soil ecosystem ~~the regime (i.e.~~is energy-limited or water-~~-~~limited~~ system)~~. ~~The observational~~

~~approach (grassland ecosystem moved to a drier and warmer site), resulted in a large decrease of precipitation (P) and non-rainfall water (NRW), an increase in actual evapotranspiration (ET_a) and upward directed water fluxes from deeper soil and hence a decline of seepage water as well a decrease in AGB and water use efficiency (WUE). The manipulative approach (grassland ecosystem treated in place) resulted in decreasing P and NRW under conditions of elevated temperature but responded with increasing NRW for elevated CO_2 as compared to the reference. Similarly, an elevated CO_2 and heating increased the ecosystem's water loss by ET_a. However, the effect of increasing CO_2 on ET_a was largely compensated by the opposite effect of an elevated temperature in the combined treatment. The seepage water rate also increased with elevated CO_2, whereas it clearly decreased for the heating treatment as compared to the reference. All treatments led to a reduction of the grassland productivity in terms of the AGB and to reduced WUE as compared to the grassland ecosystem under reference conditions.The consideration of changes in NRW and P by the treatments needs to be considered in climate change experiments to avoid an over- (elevated temperature) or underestimation (elevated CO_2) of the effects of climate change on ecosystems response, especially for sites where water limitation plays a role. The impact of drought periods on seepage rates (potentially leading to groundwater recharge) was more pronounced for the relatively humid site with a longer ET_a period without water stress than for a relatively dry site.~~

E~~An e~~levated temperature reduced the amount of non-rainfall water ~~(NRW) and precipitation (P)~~ particularly during the growing season in both approaches. In energy-limited grassland ecosystems, ~~Warming induced a decrease in P and NRW inputs despite no active control on this variables, which needs to be considered in global change experiments to avoid overestimating the effects of global warming. The~~ elevated temperature increased the actual evapotranspiration and decreased aboveground biomass ~~(AGB)~~. As a consequence, elevated temperature led to decreasing seepage rates in energy-limited systems. Under water-limited conditions in dry periods, ~~in energy-limited grassland ecosystems (excluding effects from elevated CO_2 and temperature), but~~elevated temperature aggravated water stress and thus ~~had an opposite effect on~~resulted in reduced actual evapotranspiration. ~~under water-limited conditions in drier years as a result of water stress.~~ The already small seepage rates of the drier soils remained almost unaffected under these conditions compared to soils under wetter conditions. ~~Changing climateic conditions at the land surface under elevated temperature and less P affected the amount of drainage in a similar way (i.e. reduction). However, during droughts, Rthe results of both approaches suggest that elevated temperature reduces seepage (i.e. groundwater recharge) in energy-limited grasslands (except for elevated CO_2), but not necessarily under water-limited conditions, where soil water resources are already depleted.~~ Elevated atmospheric CO_2 reduced both actual evapotranspiration and aboveground biomass in the manipulative experiment and therefore led to a clear increase and change in seasonality of seepage. As expected, ~~The response in functional relationships among hydroclimatological and ecohydrological indicators were similarly~~ differently ~~affected by changes in temperature, atmospheric CO_2 concentrations, and incoming atmospheric water (P and NRW)precipitation in both manipulative and observational climate change experiments~~. ~~T~~the aboveground biomass productivity and ecosystem efficiency indicators of the water-limited ecosystems were negatively correlated with an increas~~ing~~e in aridity~~.~~, ~~whereby~~ while the ~~energy-limited ecosystem did not show any clear relationship~~trend was unclear for the energy-limited ecosystems. ~~The results suggest that other factors than climate conditions played under energy-limited conditions a more crucial role for the efficiency and productivity of grassland ecosystems.~~

In both experimental approaches, the responses of soil water fluxes and biomass production mainly depend on the ecosystems' status with respect to energy or water limitation. To thoroughly understand the ecosystem response to climate change and be able to identify tipping points, experiments need to embrace sufficiently extreme boundary conditions as well as explore responses to individual and multiple drivers such as temperature, CO$_2$ concentration and precipitation including non-rainfall water. In this regard, manipulative and observational climate change experiments complement one another and thus should be combined in the investigation of climate change effects on grassland.

~~except for the responses of ET$_a$ and AGB in the dry and warm year 2018. The resulting response differences between the two climate change approaches were explained by the actual soil moisture status. The results suggest that energy limited ecosystems tend to increase their ET$_a$ and AGB production (excluding effects from elevated CO$_2$ and temperature), but water limited ecosystems respond with a decrease in ET$_a$ as a result of water stress, which leads to a clear decline of AGB. The We conclude from our results comparison also suggest that climate change experiments should account for the possible changes of the hydrological status of the ecosystem and impose sufficiently extreme levels of climatic conditions within their set-up to allow such changes to occur for capturing the full response of the ecosystem. In addition, we suggest to combine the strength of both approaches in future climate change studies to overcome existing experimental limitations The results may help to better understanding the impact of climate change on future ecosystem functioning and potential tipping points of ecosystems.~~

1 Introduction

Current and future climate change is expected to alter air temperature, CO$_2$ concentration in the atmosphere as well precipitation (P; Abbott et al., 2019; IPCC, 2018). Changes in these conditions will alter hydrological processes and affect the soil water availability, which is of critical importance for the agricultural sector in terms of plant development and food production (Thornton et al., 2014). ~~The agricultural management in form of g~~Grassland ~~is~~ represents one of the Earth's ~~most~~ main~~important~~ biomes (Blair et al., 2014). Managed grassland areas are important for carrying capacity of livestock as well as for herbage and hay production for forage. Moreover, these areas are also important for several other ecosystem services beside food production like water supply and flow regulation, erosion control, climate mitigation, pollination, carbon storage as well as cultural services (Bengtsson et al., 2019). However,~~All these~~ services are strongly dependent on weather and climate conditions and thus potentially highly vulnerable to climate change (Gobiet et al., 2014). Since the late 19th century, air temperatures in the Alpine region have risen about twice as much as the global or Northern Hemispheric average (Auer et al., 2007). These strongly changing climatic conditions, in particular the expected increase in frequency and magnitude of extreme events such as droughts and heavy rainfalls, ~~are likely~~potentially have adverse effects on the soil water balance ~~of grassland ecosystem and/or adverse or possibly beneficial effects on grassland~~and biomass production of grasslands, especially in mountainous regions. Depending on the regional- climate change and its local impacts, altered ~~precipitation~~ P regimes and higher temperatures potentially will increase actual evapotranspiration (ET_a) and thus negatively affect the local ecosystem services related to water (Schirpke et al., 2017; Rahmati et al., 2020). ~~The influence of droughts and higher temperature on grassland biomass production is less clear but~~ In addition, a shift in the temperature regime will prolong the growing season, which might change the vegetation composition, water use efficiency (WUE) of grasslands, enable a more intensified use of grassland sites (more frequent mowing) and increase the biomass production (Eitzinger et al., 2009; Tello-García et al., 2020). But this might largely depend on the hydrological status of the ecosystem, ~~i.e. energy-limited or water limited,~~ which can be characterized by the Budyko framework as energy-limited or water--limited (Budyko and Miller, 1974). For regions that are currently disadvantaged because of the climatic and topographic conditions, it may be expected that in the future ~~biomass~~ aboveground biomass (AGB) production will increase due to higher temperatures (Eitzinger et al., 2009). However, the combined effect of higher temperatures, causing increased ~~evapotranspiration~~ ET_a and the expected decrease in summer ~~precipitation~~ P also suggests more frequent and more severe occurrences of droughts (e.g. 2018 European drought; Peters et al., 2020), which may lead to a lower water ~~plant water stress and~~availability in the soil and thus adversely affect the ~~aboveground biomass (~~AGB~~)~~ production of grassland as well as the quantity and quality of the drainage water (Herndl et al., 2019).

To contribute to the assessment of climate change impacts on mountain grassland, there is the general need to understand the individual and combined effects of changes in temperature and ~~precipitation~~ P with and without elevated atmospheric CO_2 concentrations on the water balance components (including non-rainfall water NRW; i.e. dew and fog) and the connected biomass production of mountain grasslands. ~~This implies precipitation (P), the formation of non-rainfall water (NRW; i.e. dew and fog), evapotranspiration (ET_a), seepage water as well the ecosystem productivity (i.e. AGB), in particular during droughts.~~ The use of high precision weighable lysimeter allows quantifying the water balance components of ecosystems and determining their productivity, such as ~~e.g.~~ shown, for instance, ~~in~~ by Groh et al. (2020)~~., but requires a thoroughly processing of lysimeter data by applying quality checks and data filter (Peters et al., 2017; Groh et al., 2019)~~. It may be expected that even for northern humid ecosystems ~~NRW~~ the formation of NRW temporarily gains importance in the water budget during droughts (Groh et al., 2018) and that under such extreme conditions, heat and/or water stress can cause a decrease in the AGB production of grasslands (Fu et al., 2006). To explore how ecosystems will respond to changes in environmental conditions, key hydroclimatical and ecohydrological indicators such as the precipitation use efficiency (PUE; Wang et al., 2019), the WUE (Hatfield and Dold, 2019; Groh et al., 2020), and the runoff coefficient (Chen et al., 2007) ~~can~~ have been ~~used~~ proposed to assess the impact of changing climatic conditions on the ecosystems.

To ~~address these research question of~~ identifying the response of water fluxes and AGB production to climate change in permanent grassland soil ecosystems two major approaches have been proposed.~~, data from e~~Either manipulative experiments (using multifactorial drivers) or observational experiments on environmental gradients ~~are~~ can serve ~~as one major tools~~ to explore the relationship between changing climate factors and ecosystem responses (Hanson and Walker, 2020; Song et al., 2019; Kreyling and Beier, 2013; Knapp et al., 2018). According to Yuan et al. (2017), the main difference between these approaches is the issue of association versus causality.~~, as o~~Observational approaches can identify a relationship between a set of randomly selected variables of a system under natural conditions, while manipulative approaches are more likely to identify and confirm the underlying mechanism based on measuring responses of the system by controlling certain variables. It is often assumed that manipulative or observational climate change experiments lead to similar results in ~~order to~~the assessment ~~the effects~~ of climate change impacts on e.g. the components of the water balance. However, a recent meta-analysis on climate change experiments showed that the impacts of climate change on the nutrient cycle differed among the tested approaches (Yuan et al., 2017). Knapp et al. (2018) compared the response of different grassland ecosystems on climate change from manipulative and observational climate change experiments. In particular, they~~and~~ found that both approaches achieved similar functional relationship between growing season precipitation~~P, and NRW~~ (GSP) and AGB, when the ~~growing season precipitation~~GSP was within the range of historical observations. The predictions outside the range of historic events, however, lead to non-linear relations in the AGB response ~~versus the~~to changes in ~~growing season precipitation~~GSP (Knapp et al., 2018). This clearly demonstrates the need to impose relatively extreme changes in the boundary conditions (e.g. ~~precipitation~~ P reduction) in climate change experiments in order to observe the non-linear response of the soil ~~-~~ecosystem (i.e. AGB) to changes in the climate regime (Knapp et al., 2018). We therefore hypothesize that the response of the grassland ecosystems on changing climatic conditions will differ among the two approaches, in particular, if the soil ecosystem changes from an energy-limited to a water-limited hydrological status~~because of the different hydrological status of the soil ecosystem (i.e. energy- or water limited system)~~.

The ~~main~~ objective of the present study was to test this hypothesi~~e~~s by comparing the impact of climatic factors~~e change~~ on (i) the water balance and (ii) the AGB production within and between the manipulative and observational approaches, and (iii) to identify the impact of altered climatic~~e~~ conditions on the functional relationships between water balance components, AGB, and hydroclimatical and ecohydrological indicators. Data are provided from two distinct climate change experiments, namely "Lysi-T-FACE" (Climate Impact Research on Grassland; Herndl et al., 2010; Herndl et al., 2011) and TERENO-SOILCan (TERrestrial ENnvironmental Observatories; Pütz et al., 2016). The Lysi-T-FACE experiment ~~was defined~~is denoted here as manipulative ~~climate change~~ approach and the TERENO-SOILCan as ~~an~~ observational approach. In both experiments, high precision weighing lysimeters were used to quantify the water balance components and the AGB of grassland ecosystem in mountainous regions.

2 Materials and Methods

2.1 Manipulative and observational approaches

The climate change experiment Lysi-T-FACE is an experimental concept that has been designed to enable warming grassland plots using an infrared heating system (Kimball et al., 2008), and enriching the CO_2 content of the air using a Mini-FACE system (T-FACE; Miglietta et al., 2001). This experimental set-up was implemented at an alpine grassland site in 2010 and

2011 (Herndl, 2011). The overall experimental design at this site is based on a surface response approach (Piepho et al., 2017) and includes factor combinations of two elevated temperatures and two elevated CO_2 concentrations at 24 grassland plots under open-field conditions. The Lysi-T-FACE approach at weighable lysimeters (Fank and Unold, 2007) is implemented at six of these plots. The proper functioning of the T-FACE performance has been repeatedly tested and is fully operated since May 2014 at the experimental site.

The observational approach for quantifying climate change impacts in the soil-plant system is implemented in the TERENO-SOILCan lysimeter network since 2010 / 2011 (Pütz et al., 2016; Pütz et al., 2018). Intact soil monoliths were transferred within and between TERENO observatories to expose them, apart from the observations at their original site, to other climatic conditions (space-for-time substitution; see details in Pütz et al., 2016; Groh et al., 2020). The concept of the space-for-time substitution means that soils were translocated in space instead of waiting at the same location for changes in climatic conditions in time. The change of the climate regime by the transfer of the lysimeters were abrupt, which implies that we are not able to detect gradual changes of the grassland ecosystem over time as suggested in standard space-for-time approach, but can account for unsuspected effects from the past (Groh et al., 2020).

2.2 Lysimeter set up

The study was conducted at three test sites (Table 1). The Lysi-T-FACE test site is located at the Agricultural Research Centre Raumberg-Gumpenstein (GS) in Austria. The experimental site is located at an altitude of 707 m a.s.l. within the Enns valley of the Austrian Alps. The mean air temperature at the site is 7.2 °C, mean annual ~~precipitation~~ P is 1000 mm; and the soil is a Cambisol. Thus, the site may be considered as representative of permanent grassland in the A~~a~~lps (Schaumberger, 2011). The grasses *Arrenatherum elatius* and *Festuca pratensis* and the leguminous species *Lotus corniculatus* and *Trifolium pratense* dominate the grassland established at the Lysi-T-FACE site. The grassland was mowed three times per year (see supplement Table S 1~~31~~), each followed by mineral fertilization (Herndl et al., 2010), and the average length of the growing season over the observation period from 2015 to 2018 was 197 days (more details on the method see chapter 2.3 and Table S 2).

At GS six lysimeters are installed; one lysimeter is operated under ambient conditions (C0T0), two under a constant warming of 3 °C of grassland (C0T2) relative to the ambient surface temperature, two under a constant elevated CO_2 concentration (300 ppm) relative to the ambient atmospheric CO_2 concentration (C2T0), and one with a combination of elevated temperature and elevated CO_2 (C2T2). The used abbreviations C and T within the treatments stand for CO_2 and temperature and the numbers 0 for ambient and 2 for elevated conditions. A mechanical snow cover separation system (METER Group) is used to maintain a correct water balance in winter months. Manual snowpack separation is only required in periods with a very high snowpack. A nearby weather station was used to obtain meteorological observations of reference ~~precipitation~~P (tipping-bucket method; Young GWU), air temperature, air humidity, solar radiation, net radiation and wind speed at a height of 2 m above ground. Data from the weather ~~se~~ station~~s~~ was used to calculate grass-reference ~~ET~~evapotranspiration (ET$_0$) according to Penman-Monteith (Allen et al., 2006).

The two other test sites are part of the TERENO-SOILCan lysimeter network, ~~are~~ located in the Northwest of Germany, in Rollesbroich (RO) and Selhausen (SE). Both sites have a humid temperate climate with an average annual air temperature of 8 °C and 10 °C and an average annual ~~precipitation~~ P of 1150 mm and 720 mm for Rollesbroich and Selhausen, respectively. The plant community consists mainly of *Lolium perenne* and *Trifolium repens*. The grassland lysimeters at both sites were subject to management (cutting and fertilizer) according to the local agricultural management of the surrounding field at Rollesbroich. This includes three to four cuts per growing season (supplement Table S1) and three to four times application of liquid manure or mineral fertilizer per year (Pütz et al., 2016). Mean length of the growing season over the observation period was 208 and 243 days in RO and SE, respectively.

~~The three test fields are equipped with high precision weighable lysimeters with the similar design (METER Group). At GS six lysimeters are installed; one lysimeter is operated under ambient conditions (C0T0), two under a constant warming of 3 °C of grassland (C0T2) relative to the ambient surface temperature, two under a constant elevated~~ ~~CO$_2$~~ ~~concentration (300 ppm) relative to the ambient atmospheric~~ ~~CO$_2$~~ ~~concentration (C2T0), and one with a combination of elevated temperature and elevated~~ ~~CO$_2$~~ ~~(C2T2). The used abbreviations C and T within the treatments stand for~~ ~~CO$_2$~~ ~~and temperature and the numbers 0 for ambient and 2 for elevated conditions. A mechanical snow cover separation system (METER Group) is used to maintain a correct water balance in winter months. Manual snowpack separation is only required in periods with a very high snowpack. A nearby weather station was used to obtain meteorological observations of reference precipitation (tipping-bucket method; Young GWU), air temperature, air humidity, solar radiation, net radiation and wind speed at a height of 2 m above ground. Data from these stations was used to calculate grass-reference ET according to Penman-Monteith (Groh et al., 2019).~~

At RO (C0CL0, CL stands for climate) six lysimeters ~~and at SE (C0CL2) three lysimeters from RO~~ were installed to quantify soil water budget and AGB under ambient conditions (RO: C0CL0). At SE (C0CL2) three lysimeter were installed to quantify soil water fluxes and AGB under ~~and~~ altered ~~(SE: C0CL2, less precipitation, higher potential ET)~~ climatic conditions (SE: C0CL2, less precipitation, higher ET$_0$). A weather station (WXT510, Vaisala Oyj) was installed at both sites logging the same meteorological parameters as at GS. The reference ~~precipitation~~ P was measured with a weighing rain gauge (OTT Pluvio², OTT HydroMet GmbH) and a net radiation sensor (LP Net07, Delta OHM S.rL.) was installed above one lysimeter at each site. In addition, vegetation height observations were obtained for calculating ~~the grass-reference~~ ET$_0$ with Penman-Monteith model (Allen et al., 2006).

Table 1: Overview of the three test sites with their different approaches at the location Gumpenstein (GS), Rollesbroich (RO), and Selhausen (SE). The experiments at GS comprise treatments that have ambient (C0T0), elevated air temperature (T) (C0T2), elevated concentration of CO$_2$ (C2T0), and combined elevated concentration of CO$_2$ and T (C2T2) conditions. In the observational space-for-time substitution

approach, site RO represents ambient atmospheric demand for evapotranspiration and ambient precipitation (C0CL0).~~, while~~ T~~t~~he site SE represents elevated atmospheric demand for evapotranspiration and reduce amount of precipitation (C0CL2).

Site	Project	Approach	Treatment	Symbol
Gumpenstein (GS): 707 m.a.s.l	Lysi-T-FACE	Manipulative: Lysi-T-FACE	ambient +3.0 °C +300 ppm CO_2 +300 ppm CO_2 ; +3.0°C	C0T0 C0T2 C2T0 C2T2
Rollesbroich (RO): 511 m.a.s.l	TERENO-SOILCan	Observational: Space-for-time	Original	C0CL0
Selhausen (SE): 104 m.a.s.l	TERENO-SOILCan	Observational: Space-for-time	Translocated	C0CL2

2.3 Quantifying water balance components

Weighable high precision lysimeter systems provide measurements ~~on~~ of the components of the soil water balance equation, P, NRW, ET_a, and the vertical net flux above the lysimeter bottom (NetQ). The NetQ component comprises water flow out (Q; seepage) and into ~~(CR)~~ the lysimeter at the bottom; note the latter represent~~that CR mimics~~ upward flow by ~~the~~ capillary rise. The change in soil the water~~s~~ storage (ΔS), which affects the water availability in the soil ecosystem, was calculated as:

$$\Delta S = P + NRW - ET_a - NetQ\cancel{Q + CR} \qquad (1)$$

The water balance components P, NRW and ET_a were obtained at each site from the highly resolved (1-minute) and precise (resolution: 0.01 mm) lysimeter observations over a period of four consecutive years (2015-01-01 until 2018-12-31). ~~The water flux across the bottom boundary of the lysimeter (variable~~ NetQ~~)~~ was obtained at the same time interval from a weighable water tank (resolution: 0.001 mm).

Lysimeter mass changes are prone to external disturbances like management operations or wind. Thus, lysimeter data of mass changes have been processed by pre- and post-processing routine to avoid that external errors and noise affect the determination and separation of water fluxes across the land surface (P, NRW and ET_a). The procedure included in a first step a visual data quality check of the one-minute lysimeter data. In a second step, ~~as well as an application of~~ the Adaptive Window Adaptive Threshold filter (Peters et al., 2017) was ~~done~~applied, which has been shown to allow the quantification of small water fluxes like dew, water vapour adsorption or nighttime ET_a (Groh et al., 2019; Kohfahl et al., 2019). Water fluxes across the land surface and bottom boundary were aggregated to 10-min time intervals for detailed analysis of precipitation, especially the identification of NRW (Groh et al., 2018), and ET_a. Gaps in the time series of measured ~~precipitation~~ P and ET_a ~~evapotranspiration~~ were filled with observations from ~~either from~~ parallel lysimeter observations. In case of missing parallel lysimeter observations, gaps in the hourly time series were filled ~~by the use of an~~using linear regression ~~model~~ between observed water fluxes ~~or from the~~ and external observations or calculations (i.e. rain gauge and ~~or in terms of the calculated grass-reference ET (~~ET$_0$~~) with the Penman-Monteith model (Allen et al., 2006),~~ ~~using the meteorological data for hourly time steps~~). Finally, all water balance components were aggregated on a daily time scale and were averaged over the number of available repetitions for each treatment. At GS the water balance components for the treatment C2T0 in 2017 and 2018 were taken only from one lysimeter due to technical problems.

The component NRW, which includes fog, dew and hoar frost formation, was determined by lysimeter mass increases between sunset and sunrise, when the corresponding rain gauge from the meteorological station did not detect ~~precipitation~~ P during the corresponding 10 minute time step (Groh et al., 2018). The treatment of the Lysi-T-FACE plots at GS, i.e. free air carbon enrichment and infrared heating together, was active only during the growing season when ~~active~~ plant growth occurs. In winter periods, CO_2 enrichment is ~~totally~~ out of operation. T~~It should be noted that t~~he CO_2 enrichment ~~in the manipulative approaches (C2T0 and C2T2)~~ is also deactivated when the soil temperature ~~in~~ at a depth of 10 cm is below 3 °C; a condition as used in the set-up at GS to define the non-growing season. However, in this work, the non-growing season is defined in a different way as described next for comparing the manipulative approach with the observational approach. In contrast to the CO_2 enrichment, the heating is not generally ~~totally~~ out of operation in winter periods, ~~heating is~~but only turned off if the snow cover is higher than 10 cm. Thus, comparison of the two treatments, free air carbon enrichment and infrared heating, is possible only in the growing season. Hence the water balance components of the different soils at the specific sites under the original and climate change conditions were compared separately for the growing season and non-growing season.

~~As a quantitative measure of the effect of changes in the climate variables,~~ T~~t~~he mean error representing the average deviation between the daily values obtained under changed conditions and those of the ambient reference ~~is~~ was calculated~~.~~ using t~~T~~he R software (R-Core-Team, 2016) and the function *me* of the package hydroGOF (Zambrano-Bigiarini, 2017)~~ were used to calculate the mean error as~~:

$$Mean\ error = \frac{1}{N}\sum_{i=1}^{N}\left(Obs_{Ti} - Obs_{refi}\right) \qquad (2)$$

where n is the number of samples and Obs_{Ti} and Obs_{refi} are the daily value on the corresponding water balance term from the treatment (subscript Ti) and reference (subscript refi). The AGB production of the grassland ecosystem were analysed solely for the growing season. A thermal based definition of the growing season and non-growing season proposed by Ernst and Loeper (1976) was employed in this study to identify the beginning and ending of the growing season /non-growing season at the corresponding site. In this approach the beginning of the growing season can be obtained by adding up all positive average daily air temperatures from January 1st ~~up~~ and considering specific weight factors for each month. The daily means of air temperatures are multiplied by weighting factors of 0.5 (January), 0.75 (February), and 1 (March) and added. The beginning of the growing season in spring was defined as the day when the cumulative temperature sum exceeded a threshold of 200° C.

The same approach is used to obtain the end of the growing season, yet starting the temperature sums backward from December 31, with weighting factors of 0.5 and 0.75 for December and November, respectively.

2.4 Budyko plot

The Budyko framework (Budyko and Miller, 1974) was used to obtain information about the hydrological status of the corresponding soil ecosystem. The Budyko plot characterizes how the aridity index (AI = ET_0/P) controls the fraction of P into evapotranspiration (evaporative index EI = ET_a/P) and runoff (Berghuijs et al., 2020). In case of values of AI < 1 the system can be described as a demand ~~limited~~ (i.e. energy-limited) and in case of of AI > 1 as supply (i.e. water) limited~~ system~~. Please note that instead of considering P alone in the Budyko framework, we have also used NRW inputs here.

2.~~4~~ 5 Hydroclimatological and ecohydrological indicators

The dry matter AGB was gravimetrically determined with a precision balance~~ at both sites~~ (Gumpenstein: EA 6DCE-I, Sartorius; Selhausen and Rollesbroich: EMS 6K0.1, KERN). At GS AGB were dried ~~after drying~~ at 55°C for 48 hours, at RO and SE at~~ for dry AGB at GS and~~ 60°C for 24 hours.~~ at RO and SE.~~ The AGB from the different cuts were summed over the growing season to annual values ~~for each test site~~ and averaged over the replicated~~ions~~ treatments ~~. were calculated to compare the productive between the different treatments and climate change approaches (~~(see Table 1).

The crop WUE, defined here as the amount of dry AGB produced per unit of water used by a plant (Tello-García et al., 2020), was estimated as:

$$WUE = \frac{AGB}{ET_a} \tag{3}$$

where AGB represent the dry matter biomass production (g m^{-2}) and ET_a the actual evapotranspiration (mm) during the growing season of the corresponding year and ~~corresponding (, both of which were obtained by averaging over the lysimeters with the same~~ treatment~~s)~~. The annual PUE (g m^{-2} mm^{-1}), which are defined as the ratio of AGB and mean annual P (Zhou et al., 2020) and NRW was calculated as:

$$PUE = \frac{AGB}{P+NRW} \tag{4}$$

The PUE is a key indicator that explains the response of the ecosystem productivity to P (Wang et al., 2019) and NRW. Hence, PUE is used here to explore how the relationship between water balance and the crop components in the carbon cycle reacts to changes in the environmental conditions (Zhou et al., 2020).

The aridity index (-~~mm a^{-1}~~) and the ratio of seepage (Q) to P and NRW (-) were determined by equations (5) and (6):

$$AI = \frac{ET_0}{P+NRW} \tag{5}$$

$$QP = \frac{Q}{P+NRW} \qquad (6)$$

The QP ratio is a dimensionless indicator that describes the portion of P and NRW that becomes seepage ~~that~~ and eventually will contribute to groundwater recharge. Here, we used QP ratio as indicator to assess how changing climatic~~e~~ conditions affect the hydrological functioning of the ~~similar~~ soil~~-~~ ecosystem.

It should be noted that for QP, AI, and PUE normally only P is used, as quantitative information on NRW are often not available. Linear correlations between AGB, ET_a, ET_0, WUE, GSP, PUE, and AI were generated by the use of the package *lm* (R-Core-Team, 2016) to determine the responses of the corresponding variable/indicator under changing climate and the reference conditions ~~for~~ of the manipulative or~~and~~ observational approach. The significance level ($p < 0.01$) was used to indicate if the relationship between the variables are statistically significant.

3 Results~~ and discussion~~

3.1 Impact on the water balance components

3.1.1 Precipitation and non-rainfall water

The average annual P for the manipulative climate change approach at GS ranged from 1088 to 1131 mm a^{-1} across the observation period (2015 – 2018; Table 2; more details in Table S 3).~~ and for the treatments.~~ The ~~P~~ values of P were generally larger during growing (average range: 691 to 724 mm) than non-growing seasons (average range: 396 to 408 mm; Table 2). The average annual NRW ranged between 52 and 76 mm (Table 2; more details in Table S 4), which corresponds to 4.8 to 6.7 % of ~~the total annual~~ P (Table S 5). In contrast to P, NRW was on average larger during the non-growing season (34 to 48 mm) than during the growing seasons (20 to 28 mm).~~, which agrees well with previous findings on the seasonality of dew formation across different climate zones (Zhang et al., 2019; Groh et al., 2019; Atashi et al., 2019).~~ The treatments at GS showed differences in P and NRW, despite no active direct control on these variables. The lysimeters solely enriched with CO_2 (C2T0: 1131 mm) achieved on average similar annual P amounts over the observation period than the reference lysimeter (C0T0: 1125 mm). In contrast, the annual P amounts of the temperature-increased treatment (C0T2: 1096 mm) and the combined CO_2-enriched and temperature-increased treatment (C2T2: 1088 mm) were on average smaller than the reference observation (C0T0). A similar tendency on daily P between the treatments and the ambient measurement was observed for the non-growing (Fig. 1 A) and growing season (Fig. 1 B), with negative mean error values for treatments C0T2 and C2T2 and positive values for C2T0. Most pronounced differences between treatments with an elevated temperature and reference were detected during the growing season and the mean error of daily P ranged between -0.12 to -0.14 mm d^{-1} (Fig. 1 B). ~~This demonstrates clearly a warming-induced decrease in GSP (by up to 4 %) and NRW amounts (up to 24 %), which needs to be considered in global change experiments to avoid overestimating the effects of global warming. This agrees well with Feng et~~

~~al. (2021), who showed that heating with an infrared heater system reduced dew formation for an alpine grassland ecosystem of the Tibetan Plateau.~~

Table 2: Average values of the soil water balance components: precipitation (P), non-rainfall water (NRW), actual evapotranspiration (ET_a), net water flux across the lysimeter bottom (NetQ), and change of the soil water storage (ΔS). The values were averaged across the non-growing seasons, growing seasons and annual values for the period 2015 - 2018, from replicated lysimeter measurements at each test site~~s~~: Gumpenstein (GS) with C2T0 (CO_2: +300 ppm; two lysimeter), C0T2 (temperature: +3°C, two lysimeter), C0T0 (ambient, one lysimeter), C2T2 (CO_2: +300ppm, and temperature: +3°C, one lysimeter), Rollesbroich (RO) with C0CL0 (original, six lysimeter) and Selhausen (SE) with C0CL2 (translocated, three lysimeter).

Component	Season	Gumpenstein				Rollesbroich	Selhausen
		C2T0	C0T2	C0T0	C2T2	C0CL0	C0CL2
		mm					
P	non-growing	407.6	400.8	405.8	396.2	516.0	212.6
	growing	723.7	695.3	718.9	691.4	503.8	401.7
	annual	1131.3	1096.1	1124.7	1087.6	1019.8	614.3
NRW	non-growing	48.1	36.7	39.9	33.5	30.9	21.6
	growing	28.2	19.5	24.7	18.8	24.8	22.8
	annual	76.3	56.2~~1~~	64.6	52.3	55.7	44.4
ET_a	non-growing	114.9	133.7	109.6	125.0	87.3	88.7
	growing	541.6	696.8	620.2	645.0	552.0	596.1
	annual	656.5	830.5	729.8	770.0	639.3	684.8~~7~~
NetQ	non-growing	351.5	272.3	326.0	285.3	429.4	30.0
	growing	201.4	54.5	122.1	61.9	28.3	-58.2
	annual	552.9	326.8	448.1~~0~~	347.2	457.7	-28.2
ΔS	non-growing	-10.7	31.5	10.1	19.4	30.2	115.5
	growing	8.9	-36.5	1.3	3.3	-51.7	-113.4
	annual	-1.8	-5.0~~1~~	11.4~~5~~	22.7	-21.5	2.~~2~~1

All treatments had a visible impact on the formation of dew in comparison to the ambient conditions (C0T0; Table 2). ~~The tendency of the different treatments on NRW was similar to P, with C2T0 values generally larger and C0T2 and C2T2 smaller compared to the reference.~~ Observations reveal that an increase in canopy surface temperature (C0T2 or C2T2) goes along with a decreasing formation of NRW with negative mean error values during both periods (Fig. 1 E and F). The change in temperature and CO_2 concentration~~s~~ reduced the annual NRW on average for C0T2 by 13 % and for C2T2 by 19 % in comparison to the ambient variant C0T0. Results for C2T2 indicate~~s~~ that the elevated surface temperature is the dominating factor in dew formation.~~ , as ~~T~~t~~his treatment generally achieved the lowest relative contribution of ~~dew formation on the total incoming water~~NRW at the annual scale and the largest negative mean error values. Our results reveal that an elevated CO_2 concentration also seems to influence the formation of NRW, as ~~the~~ NRW increases by 18 % for treatment C2T0 compared to the reference C0T0. ~~One reason might be that an increasing airflow above the canopy during the CO$_2$ application reduces the canopy temperature, increases the temperature gradient between canopy and air, thus enhancing dew formation. This agrees well with Feng et al. (2020), who reports that artificial warming of surfaces can reduce the amount of dew by up to 91 % in arid to semi-arid grassland ecosystems, which demonstrates that the effect of infrared heater warming system are an often overlooked factor in warming experiments. Not considering these effects of elevated warming and elevated CO$_2$ on NRW and P in manipulative climate change experiments may lead to an under- or overestimation of ecosystem responses to changes in P and NRW in climate change simulation studies.~~

Seasonal and annual ~~P~~ values of P and NRW amounts were generally significantly lower for 2018 compared to the other three years (Table S 3 and S 4). However, the ~~percentage~~ relative contribution of NRW ~~achieved on average with 5.7 % of the annual~~to P ~~a~~ is similar ~~contribution as observed during~~to the previous years. ~~The quantitative contribution of NRW to the soil water balance can become important for crop production, especially under water-limiting conditions, because many ecosystems in Europe were largely affected by the extreme weather conditions in 2018, which were associated with a decrease in Northern European crop production (i.e. drought, heat wave; Beillouin et al., 2020).~~

The annual P at the observational site RO was in general lower in the growing seasons (average range: 388 to 569 mm) than during the non-growing seasons (average range: 484 to 581 mm~~; Table S 3~~4). Similar to GS, the lysimeters from RO in SE obtained higher ~~P~~ values of P in growing seasons (average: 402 mm) than in non-growing seasons (average: 213 mm). The transfer of lysimeter brought the soil ~~-~~ecosystem from a region with high (RO) to a region with low ~~mean~~ P (SE).~~,~~ ~~which consequently led to a reduction of~~As compared to RO, the average annual P at SE is lower by 406 mm (i.e., a decline of 40 %) and ~~to~~ there is a shift in the seasonal P distribution, with higher P during the growing season. According to the Budyko framework, the change in P and the higher ET$_0$ in SE lead to a shift from an energy-limited (RO) to a water-limited regime (SE) with values for AI larger than one (Fig. 2). The latter one is important, as the soil ~~-~~ecosystems at the two sites are characterized by ~~a~~ different soil water dynamics at the beginning of the growing season. Daily P values in C0CL2 on average were ~~on average -~~1.57 and ~~-~~0.76 mm ~~-~~per day smaller during the non-growing and growing season, compared to C0CL0 (mean error, Fig. 1 C and D).

The annual average NRW was 20 % larger for C0CL0 (55.7 mm) than for C0CL2 (44.4 mm, Table S 4).~~,~~ ~~but~~ However, the amount of water from~~overall contribution of~~ NRW relative to P was higher for C0CL2 (7.2 %) than for C0CL0 (5.5 %, Table S 5). The seasonal distribution of NRW at RO and SE shows, similar to GS, larger values of NRW during non-growing seasons. The mean daily deviation of NRW between RO and SE was similar during the non-growing and growing season (-0.03 mm). Larger differences were found during winter, when snow covered the grassland at RO (i.e. no measurements on P and NRW possible) whereas~~meanwhile~~ in SE~~,~~ NRW inputs could be determined (Fig. 1 G).

The lowest annual P values of the observation period 2015-2018 were observed in the drought year 2018 with 872 mm at RO and 485 mm at SE (Table S 3). Similarly, also relatively small NRW values ~~could be~~were observed ~~in 2018~~ at both sites in 2018 (RO: 45 mm; SE: 38 mm). Despite the lower NRW inputs in 2018, the ~~contribution~~ amount of water from NRW relative to P ~~achieved~~ was 7.9 % at SE, which is the highest value during the observation period. Again, this demonstrates the importance of NRW inputs ~~for soil-ecosystem~~ in dry years when ~~P in form of~~ rainfall ~~P~~ is low.

~~A direct comparison of P between the manipulative and observational approach was difficult, because only the observational approach includes explicitly a change of P within its design. However, including a change of P, especially during the growing season, is important for climate change studies as the inter-annual variability of the ecosystem productivity (i.e. AGB) are strongly correlated (Knapp et al., 2018). Hence, climate change experiments that contain information how altered P patterns and droughts affect ecosystem response (i.e. ET_a, AGB) would be helpful to further understand how ecosystems will react under conditions with less plant-available soil moisture. However, despite no active control on P within the manipulative approach, treatments with an increased surface temperature affected not only the formation of NRW but also the amount of P. Here, the effect of local warming on the relative humidity and temperature of the air within and above the canopy could play an important role, as these influence the vapour pressure gradient between the air inside the leaf and the canopy, which in turn affects evaporation (soil and surface) and transpiration. At least for NRW, both climate change experiments found similar patterns and could show that NRW inputs decline when accounting for an increase in temperature (Table 2; Fig.1 E to H), but their relative contribution to P was only larger under the observational approach (Table S 5). This decline of NRW agrees well with Tomaszkiewicz et al. (2016), who predicted a decline in dew formation for forecasted trends of increasing temperature and relative humidity under future climatic scenarios for the Mediterranean region.~~

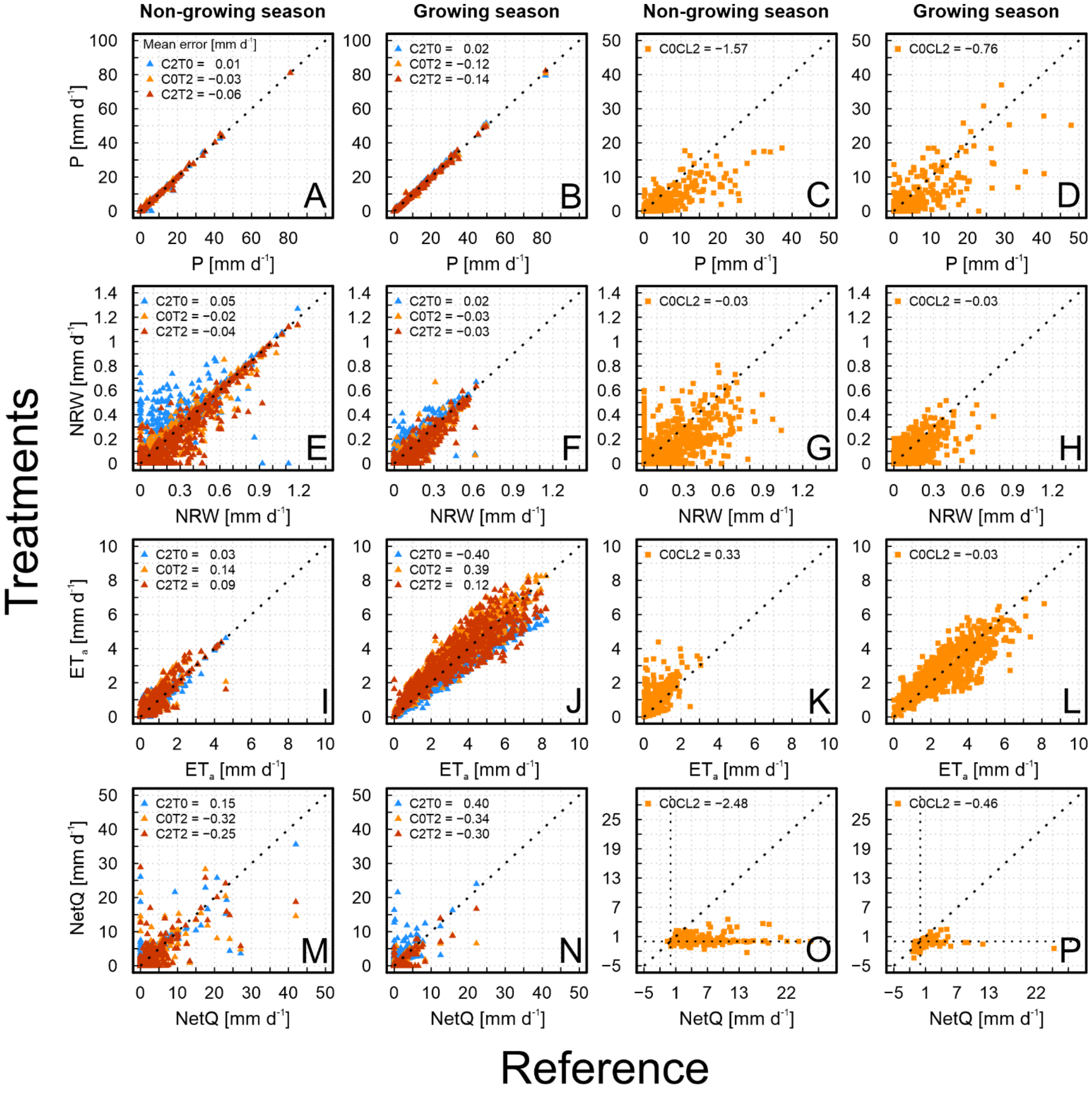

Figure 1: Comparison of all soil water balance components for all ~~different~~ treatments, or sites of the two ~~different~~ approaches (Lysi-T-FACE: C2T0, C0T2, C2T2: TERENO-SOILCan: C0CL2) to ambient reference of the two ~~different~~ approaches (Lysi-T-FACE: C0T0; TERENO-SOILCan: C0CL0). Subplot A, B, C and D show the daily precipitation (P) of the treatments against the reference observation for the non-growing and growing season (2015 to 2018) for the manipulative (A and B) and the observational experiment (C and D). The same is shown for the non-rainfall water (NRW) in subplot E, F, G, and H, for the actual evapotranspiration (ET_a) in I, J, K, and L, as well as for net water flux across the lysimeter bottom (NetQ) in M, N, O and P. Average daily values were obtained from replicate lysimeter of the same treatment or site. The mean error (mm d^{-1}) was calculated to express the average deviation between the daily values obtained under changed conditions and those of the ambient reference.

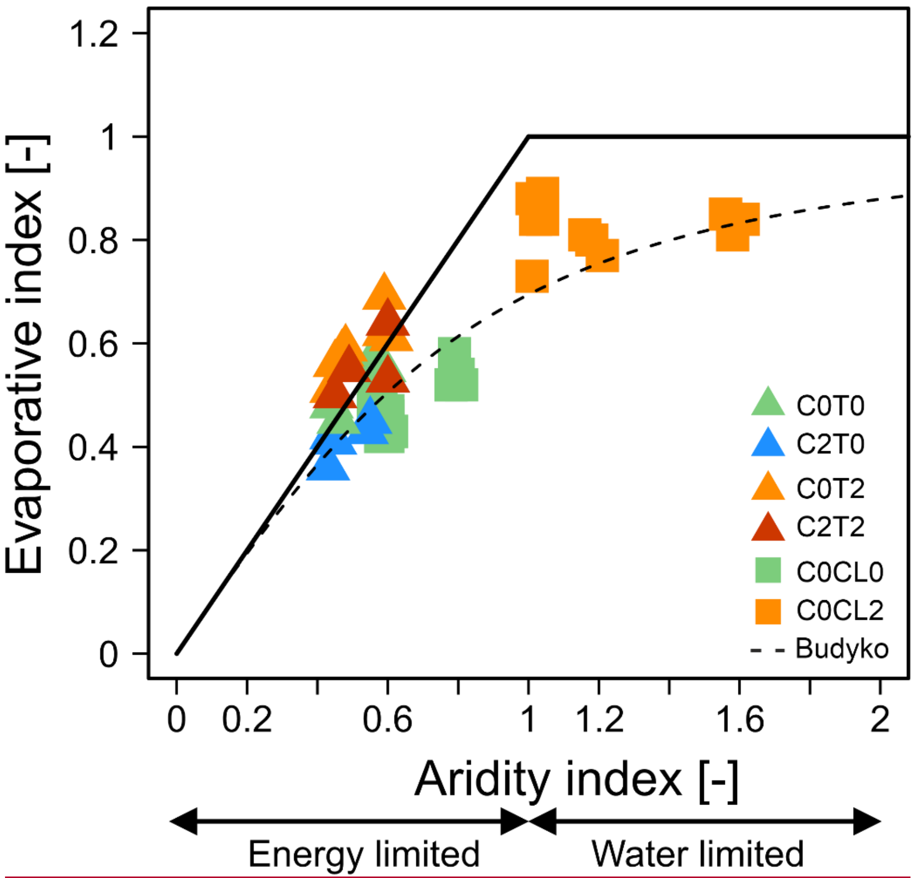

Figure 2: Budyko plots for the two -approaches (Lysi-T-FACE: C2T0, C0T2, C2T2: TERENO-SOILCan: C0CL2) to ambient reference of the two approaches (Lysi-T-FACE: C0T0; TERENO-SOILCan: C0CL0) during 2015-2018. The aridity index and evaporative index are the ratios of the cumulated yearly grass reference evapotranspiration and actual evapotranspiration to the incoming atmospheric water (i.e. precipitation and non-rainfall water). The dotted curve shows the Budyko curve (ω = 2.6).

3.1.2 Evapotranspiration

The average annual ET_a for the manipulative approach at GS ranged between 657 and 831 mm among the different treatments and reference during the observation period (Table 2, more details in Table S 6). The average difference between the treatments in the non-growing season were relatively small (max. 24 mm per period) in comparison to the growing season (max. 155 mm per period; Table 2; Table S 6). During ~~the~~ time periods with an active control on CO_2 and surface temperature, treatments largely differed from the reference observations. Compared to the reference, ~~T~~the average daily ET_a ~~decreased under~~of the treatment with CO_2 enrichment (C2T0) decreased by ~~-~~0.40 mm, whereas that of ~~and~~ the treatment with an elevated surface temperature (C0T2) increased ~~the daily ET_a on average~~ by 0.39 mm ~~in comparison to the reference ET_a~~ (Fig. 1 J). ~~Thus, an~~

~~elevated CO_2 and increased temperature results in contrasting impact on the ET_a of grassland soil-ecosystems, because of their opposing individual effects on transpiration (Sorokin et al., 2017). Plants respond to elevated atmospheric CO_2 concentrations with a reduced stomatal opening and an increase in photosynthesis (Kruijt et al., 2008; Ainsworth and Rogers, 2007), which in combination lead to an enhanced plant WUE (Hovenden et al., 2017). In contrast, elevated temperatures can lead under non-water limiting conditions to an increase in transpiration due to an rise in vapour pressure deficit and thus enhanced evaporation, because warmer air can retain more moisture (Kirschbaum and McMillan, 2018); however, it was still unclear which effect has more impact on ET_a. Kirschbaum and McMillan (2018) suggested for a range of locations from tropical to boreal forest that elevated CO_2 concentrations had a stronger transpiration-depressing effect than elevated temperatures. Lenka et al. (2020) showed that treatments with an elevated CO_2 concentration as well as combined increase of CO_2 and temperature reduced the stomatal conductance, lowered the ET_a, and consequently improved WUE of soybeans.~~ Our results for the combined treatment C2T2, in general (despite 2018), showed larger daily ET_a values in comparison to the reference, but the average deviation was only 0.12 mm. ~~This result suggests that the effect of elevated CO_2 to reduce ET_a was largely compensated by the effect of elevated temperature in the combined treatment C2T2. A further comparison of WUE between the treatments could help to clarify which effect was more important for the grassland ecosystem. Kirschbaum (2004) suggested that the effect of CO_2 on ET_a is more pronounced for C3 plants under water limited conditions and at higher temperatures (Kirschbaum, 2004), because it enhanced the WUE of the plant (Kirschbaum and McMillan, 2018). However, its effect under non-water limited but temperature limited growth conditions on plants is still unclear. As compared to the previous years, the ET_a patterns changed during~~In the growing season of the exceptionally dry and warm year 2018, the ET_a response to treatment ~~patterns~~ changed as compared to the previous years. For C2T0, the growing season ET_a in 2018 showed an increase by 42 mm compared to average values from previous years (2015 to 2017)~~,~~. Despite the observed increase relative to previous years, C2T0 still showed the lowest ET_a rates of the treatments in 2018. ~~whereas it declined~~ F~~f~~or C0T2 and C2T2, ET_a in 2018 was lower than ~~in comparison to~~ the average of the previous years (~~by~~ 46 and 80 mm, respectively). This decline suggests that ET_a at the heated plots was temporarily limited by the low soil water availability ~~and~~ resulting from a decrease in soil water storage ~~of water~~ in 2018. In contrast, ET_a of the reference C0T0 did not differ in the growing season 2018 from the average ET_a values of the previous years 2015 to 2017.~~, which~~ This demonstrates that the ET_a ~~of soil-ecosystem~~ at the reference plot was not limited by water (Fig.2). ~~Despite the observed increase relative to previous years, C2T0 still showed the lowest ET_a rates of the treatments in 2018. This lower ET_a indicates that an elevated CO_2 can mitigate effects of summer droughts on alpine grasslands, which agrees well with Inauen et al. (2013). They showed that elevated CO_2 reduced ET_a by up to 7 % across a range of different grassland types in the central Swiss Alps.~~

The annual average ET_a of the observational approach was lower at RO (639 mm) than at SE (685 mm; Table 2). The length of the growing season increased on average by 36 days over the observation period due to the translocation ~~of the grassland soil-ecosystem~~ from RO (C0CL~~T~~0) to SE (C0CL2). Compared with the reference C0CL0, the average daily ET_a of C0CL2 was lower by 0.03 mm in the growing season and larger by 0.33 mm in the non-growing season (Fig. 1 K-L). Interestingly, during the 2018 European drought-affected growing season, average daily ET$_a$~~grassland~~ responded with an increase of 4% for C0CL0~~ in terms of daily ET$_a$~~, while~~ the daily average ET$_a$ of~~ ~~C0CL2~~ it decreased for C0CL2 by 18% in 2018 compared to ~~ET$_a$ of~~ the previous years. ~~A similar reduction of ET$_a$ across different ecosystem types could be observed for the sites in Europe affected by this drought in 2018 (i.e. forests, grasslands, croplands and peatlands; Graf et al., 2020). Our results reveal that the limitation in plant available water at site SE increased during the drought and the heat wave intensified the water stress and thus significantly reduced grassland ET$_a$. This reduced ET$_a$ rate is in contrast to findings from the manipulative approach (Fig. 1 J), were treatments with an elevated temperature increased ET$_a$ in comparison to the reference. Main reason for this contrasting response among the different climate change approaches is that the grassland soil-ecosystem from the observational approach was shifted from a rather energy limited to a water limited regime due to the transfer from RO to SE (Rahmati et al., 2020), whereas the regime at GS is mainly energy limited.~~

3.1.3 Seepage ~~water~~ and ~~change~~ soil water storage

The ~~values for the measured~~ water flux across the lysimeter bottom (NetQ) of C2T0 was ~~are~~ larger ~~as compared to~~than that of the reference C0T0 at GS (Figs. 1 M and 1 N). As expected, this difference is most pronounced~~Especially~~ during the growing seasons when the physiological effect of CO$_2$ enrichment reduces ET$_a$ ~~, the seepage water of C2T0 was during the growing season 2015 up to 143 % higher than that of C0T0~~ (Table S 7). Elevated CO$_2$ ~~levels~~ (i.e. C2T0) thus appears to affect the observed seasonality of seepage through the~~ir positive impact on~~ reduction of ET$_a$ in the growing season~~ (reduction), as the differences for NetQ between the growing and non-growing seasons are relatively low compared to all treatments or reference~~. ~~Vice versa~~In contrast, the seepage of the treatments C0T2 and C2T2 ~~achieved seasonally lower values of seepage water~~was lower than that of C0T0 both in the growing and the non-growing periods (see values in Table S 7 and~~ and thus clearly~~ the negative mean errors ~~(< -0.34 mm d^{-1};~~in Fig. 1 M and N)~~ during both periods~~. Thus,~~is demonstrates that~~ water savings due to ~~an~~ elevated CO$_2$ resulted in a significant increase of seepage ~~water~~ (23 % compared to the reference), whereas ~~treatments with~~ higher temperature~~s~~ reduced seepage ~~, i.e.~~ (for C0T2 ~~(~~–27 %~~)~~ and for C2T2 ~~(~~–23 %~~)~~ compared to the reference)~~, clearly reduced the seepage water seasonally up to 69 % in comparison to the reference (Table S 7)~~. Likewise, different effects of the treatments are apparent in the changes of the soil water storage (ΔS) during the growing season (Table S 8). C0T2 showed a depletion of the soil water storage in the growing seasons of all years, whereas the other treatments tend to positive values of ΔS in the growing season. An exception is the drought year 2018, where an increase of soil water storage during the growing season was observed only at C2T0. Also, the combined treatment C2T2 shows less depletion of the soil water storage than the reference in the growing season of 2018. This suggests that the aforementioned water savings due to CO$_2$ enrichment are particularly effective under drought conditions~~during the growing seasons. Previous investigation for a grassland at the Swiss Alps showed only a slight increase of seepage water under elevated atmospheric CO$_2$ (Inauen et al., 2013). These changes in seasonal seepage water could affect the catchment runoff, which is important for hydropower productivity and profitability in Alpine regions (Anghileri et al., 2018).~~

Impacts of the ~~The~~ European drought in 2018 ~~was~~ were also clearly visible ~~as~~ in the measured NetQ ~~of all observations~~ during the growing season, which were ~~was reduced to almost~~nearly zero at all treatments (Table S 7). ~~Comparing~~ Compared to the ~~growing season NetQ in 2018 with the~~ averages ~~NetQ values~~ of the previous years, ~~a severe decline of NetQ, ranging~~the seepage in the growing season 2018 decreased between 95 to 98 %~~ over all observations was found~~. This suggests that the seepage and thus groundwater recharge at such alpine grassland sites was considerably~~e~~ affected by the 2018 drought. Interestingly, the water saving effect of CO_2, which was found to mitigate the depletion of the soil water storage under drought (Table S 8), was not evident in the seepage rates observed in 2018 (Table S 7).

The NetQ from the observational approach showed extreme differences between the seasonal values over the observation period. Largest difference in NetQ between C0CL0 and C0CL2 were observed especially during the non-growing season (mean error of -2.48 mm; Fig, 1 O). In comparison to the reference C0CL0, ~~The~~ NetQ of C0CL2 ~~changed in comparison to the reference C0CL0~~ on average changed by -106 %. This demonstrates that for the water-limited site at SE ~~that~~ the rewetting in the non-growing season is not sufficient to contribute to NetQ and hence water from P and NRW are mainly used to refill the depleted soil ~~-~~water storage. This is confirmed by the increase of soil water storage during the non-growing season, which on average is much larger at SE (116 mm) compared to RO (30 mm). Values of NetQ during the growing season were always negative for C0CL2, which ~~emphasizes~~ indicates an upward directed ~~water~~ flow from deeper soil ~~layer~~ or groundwater (Table S 7). However, the upward direct water fluxes did not compensate losses of water by ET_a and thus on average resulted in a clear depletion of the soil water storage at RO (-52 mm) and SE (-113 mm; Table S 8) in the growing season. ~~The severe decline in groundwater recharge during the drought 2018, especially the NetQ decline during the growing season by 159 % at RO, will eventually also affect stream waters. Although stream flows are partially buffered by groundwater, the reduced recharge will deplete regional water storage reserves as shown by Fennell et al. (2020) for a catchment in 2018 in Scotland.~~ During the drought in 2018, RO showed, similar to GS, a significant decrease in NetQ. ~~In contrast~~However, the ~~soil-ecosystem in SE showed only low~~ impact ~~of the dry conditions in 2018~~ on NetQ at SE (-20 mm) was low compared to observations from the previous years (-31 mm). This was mainly related to large amounts of P during the autumn and winter months of 2017, which caused a much faster refill of the soil ~~-~~water storage (Table S 8) in comparison to other years and consequently a ~~larger~~ higher ~~NetQ~~ seepage that compensated the larger upward directed water flux at the site during the drought in 2018. ~~Long-lasting droughts can affect the soil-water storage even in the following year, if winter P is not able to fully replenish the depleted soil water storage (Riedel and Weber, 2020). Thus, we expect the largest effect on NetQ of the 2018 drought at those sites in the following year.~~

~~The response of NetQ to changing climatic conditions was similar for all approaches (excluding C2T0; Fig. 1 M to P). The decrease of NetQ underlines that the physical and biological response of the ecosystem to changing climatic conditions will control water fluxes over the land surface, as warming of land surface, reduced precipitation, increased~~ ~~CO_2~~ ~~levels and higher atmospheric demand for ET, will be altered and thus reduce groundwater replenishment in the future.~~

3.2 Hydroclimatological and ecohydrological indicators

3.2.1 Aboveground biomass and water use efficiency

At GS, annual AGB ~~were~~ was largest ~~during~~ in ~~the year~~ 2016 with an average value of 845.2 g m^{-2}. The lowest AGB production was ~~quantified~~ obtained in 2015 with an average amount of 709.7 g m^{-2}. For the years 2017 and 2018, average AGB values of 821.1 g m^{-2} and 795.2 g m^{-2} were obtained (~~more details of single years in~~see Table S 9 for more details~~8~~). The year-by-year fluctuations of AGB are mainly induced by varying weather conditions at GS, as the management (cutting, fertilizer) was identical during the different growing seasons (Fig. ~~2~~ 3 A). The reference C0T0 showed on average the largest AGB (1092.5 g m^{-2}). ~~Regarding the effect of the different~~Among the treatments~~ on AGB~~, ~~the treatment~~ C0T2 ~~achieved~~ on average had the largest annual AGB (743.3 g m^{-2}) and ~~the treatment~~ C2T2 ~~with (~~635.0 g m^{-2}~~)on average~~ the lowest~~ annual AGB production~~. This reveals ~~clearly~~ that ~~a~~ the combined treatment with ~~an~~ elevated temperature and elevated CO_2 concentration (C2T2) resulted in reduced ~~the~~ grassland productivity ~~on average by 42 % in~~ compar~~ison~~ed to the reference C0T0. The average annual AGB of C2T0 (700.5 g m^{-2}) was ~~in general~~ also smaller than ~~the AGB~~that of the reference C0T0. In 2018~~The treatment with only an elevated atmospheric CO_2 (~~, C2T0~~)~~ yielded slightly ~~increased~~ higher~~the annual~~ values of AGB ~~in comparison to~~than C0T2, ~~in the dry 2018, whereas~~but for the other years ~~the~~ AGB of C2T0 was lower than that of C0T2 (Fig. ~~2~~ 3 A). ~~This reveals that CO_2 fertilization effects were only visible at GS under environmental conditions with less P and higher temperature, which agrees well with previous studies (see e.g. Morgan et al., 2004; Ainsworth and Rogers, 2007). The overall reduction of AGB of all treatments in comparison to the ambient AGB might be related to an increase of heat stress due to the treatments, which is either directly induced by an elevated canopy temperature or in case of elevated CO_2 indirectly, because higher CO_2 probably reduce evaporative cooling of plants (Obermeier et al., 2018). The results are in contrast to the widely expected positive effects of increasing CO_2 on productivity of agricultural land (Amthor, 2001; Degener, 2015; Zheng et al., 2018).~~

The negative effect of elevated temperature and elevated CO_2 concentration on the AGB ~~could~~ was also ~~be~~ seen for ~~the~~ WUE (Fig. ~~2~~ 3 C). The WUE of C2T2 ~~with (~~1.0 g m^{-3}) was on average smaller than ~~WUE~~ that of C0T2, C2T0 and C0T0 (1.1, 1.3 and 1.8 g m^{-3}). For all years, the ambient WUE was much larger than the respective WUE of the treatments. This~~, which~~ reveals a negative effect of elevated CO_2 concentration and elevated temperature on WUE for this grassland ecosystem. ~~However, comparing WUE a~~Among the treatments ~~reveals a~~the highe~~r~~st WUE was obtained for C2T0, which corresponds to the aforementioned water saving effect of elevated CO_2 (see sections 3.1.2 and 3.1.3).~~, which was shown previously for a range of different agricultural ecosystems (Nendel et al., 2009; Roy et al., 2016), because the plants could increase their assimilation rates and simultaneously reduce their water loss by decreasing stomatal conductance under an elevated CO_2 (Lammertsma et al., 2011). However, higher temperature seems to increase the "non-productive" water losses, as evident from treatment C0T2 or C2T2, which led to less efficient crop water use as compared to the unheated plots (Fig. 2 C). The small difference between WUE of C0T2 and C2T2 suggests that higher temperatures dominated the response of the grassland ecosystem under~~

~~conditions with elevated temperature and atmospheric CO$_2$ concentration (no compensation).The largest difference in WUE between C2T2 and C0T0 could be seen in 2016 and 2018~~.~~, which might be related to increasing heat stress under all treatments (Obermeier et al., 2018).~~

~~The observed AGB f~~For the observational approach, ~~achieved~~ on average a higher grassland productivity was obtained under wetter and colder conditions (C0CL0: 794 g m^{-2}~~) than under a drier and warmer climate (~~; C0CL2: 721 g m^{-2})~~.~~, The year 2015 was an ~~with~~ exception ~~of 2015~~where AGB was higher at the warmer and drier site (Fig. ~~2~~ 3 B). During this year, the larger AGB ~~was~~ mainly ~~related to the AGB~~resulted from the first cut in the season, where the grassland ecosystems of C0CL2 and C0CL0 achieved on average values of 556 and 316 g m^{-2} (Table S ~~8~~9). ~~The large differences might be related to the combined effect of moderate drought in 2015 (Ionita et al., 2016) with higher temperatures and solar radiation that led to an earlier start of the growing season for C0CL2 at SE, by meanwhile optimal water availability in spring. Values f~~For ~~AGB from~~ the other cuts, AGB ~~were~~ on average was much larger under wetter~~colder~~ and colder~~wetter~~ ~~than under warmer and drier~~ conditions (C0CL0), despite the ~~in average 36 days~~ longer growing season at the warmer and drier site SE (~~for~~ C0CL2). This was especially visible for the last cuts of the season in 2016 and 2018, when AGB was lower for C0CL2 than C0CL0. Heatwaves in 2016 and 2018 and the decrease of growing season P by 36 % in 2018 in comparison to the average values of the previous years reduced drastically the AGB of C0CL2. ~~The grassland of C0CL2 was exposed to an increasing drought intensity during this period and the plants turned slightly dry and brown and were visibly affected by drought stress in summer 2018 (Rahmati et al., 2020).~~

The WUE at the wetter ~~colder~~ and ~~wetter~~ colder climate was on average 1.53 g m^{-3} and thus clearly higher than under warm and dry conditions (1.29 g m^{-3}, Fig. ~~2~~ 3 D). These results show~~ed~~ that decreasing P and increasing ~~demand of the atmosphere for~~ ET$_0$ led to a decrease of ~~the~~ WUE by 22 %. Average differences of WUE between both sites of the ~~2nd~~ second and ~~3rd~~ third cut showed values up to 0.63 g m^{-3}~~,~~. For these two cuts, ~~which were the largest~~ differences between C0CL0 and C0CL2 were largest, ~~meanwhile~~ whereas WUE of the ~~1st~~ first cut was ~~on average rather~~ similar at the two sites (data not shown). This suggests that the difference of soil water availability between C0CL0 and C0CL2 increases within the growing season (large depletion of soil water storage at C0CL2), which affects plant growth. The exceptional drought in 2018 affected largely the WUE, as the value for last cut in 2018 was vanishingly small at C0CL2 (0.16 g m^{-3}) and ~~decreased~~ lower by 65 % in comparison to results from C0CL0. ~~The response to drought can be explained for semi-arid to humid, as opposed to arid ecosystems, with a higher sensitivity of ecosystem processes to changes in hydroclimatic conditions (Yang et al., 2016). Niu et al. (2011) showed for a semi-arid grassland from the temperate steppe in Northern China that an increase in P stimulated the WUE of the ecosystem. Similar to our finding, De Boeck et al. (2006) showed that warming of several grasslands in Belgium led to a decrease of biomass production and WUE. But the same study also implies that WUE of individual species was affected differently by warming experiment, which might led to compositional changes in the ecosystem due to shifts in the competitiveness under altered climate conditions.~~

~~Comparing the results of WUE and AGB between both approaches (Fig. 2) suggests that the impact of drought on the WUE and AGB of grasslands under ambient conditions was much larger in the lowlands than at higher altitudes. However, both approaches responded to dry conditions with a decline in AGB and WUE, except C2T0 treatments, as here CO_2 fertilization effects are critical under such environmental conditions. An elevated heat stress might explain the different response to AGB and WUE within the manipulative experiment, whereby for the observational approach additional water stress due low GSP was the main driver for changes in AGB and WUE. The response of AGB and WUE on altered climatic conditions from the manipulative and the observational approach suggests that for temperate humid grassland ecosystems, changes in P affected AGB and WUE in a similar way as elevated atmospheric CO_2 and higher temperatures. Further explorations of the distinct impact of climate change by manipulative and observational approaches should thus include changes in the P regime in addition to altered CO_2 and temperatures.~~

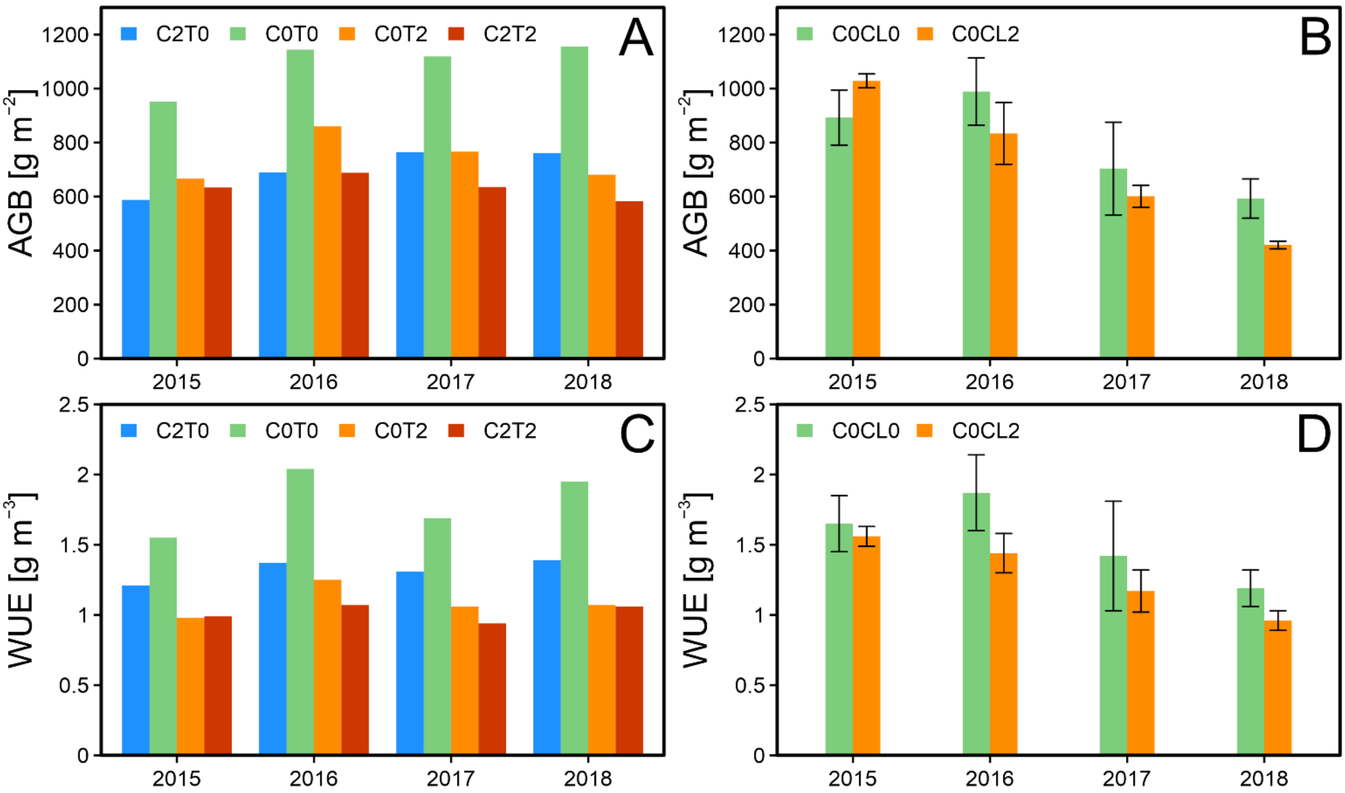

Figure 3~~2~~: Dry aboveground biomass (AGB) during the observational periods 2015-2018 for the manipulative approach Lysi-T-FACE (C2T0; C0T0; C0T2; C2T2) (A) and observational approach TERENO-SOILCan (Rollesbroich C0CL0; Selhausen C0CL2) (B) as well crop water use efficiency (WUE) for the manipulative (C) and observational approach (D).

3.2.2 Precipitation use efficiency and seepage ~~water~~ to precipitation ratio

For the manipulative approach, ~~The~~ PUE~~, which includes P as well as NRW,~~ ranged ~~for the manipulative approach Lysi-T-FACE~~ from 0.5 to 1.1 g m^{-2} mm^{-1} across the reference and the different treatments (Fig. ~~3~~ 4 A). The highest ~~PUE~~ value was ~~achieved~~ obtained under ambient conditions (C0T0) in the ~~dry~~ drought year 2018. All treatments led to a decline of PUE in comparison to C0T0 (1.2 g m^{-2} mm^{-1})~~,~~ and showed ~~on~~ the same average ~~no differences between each other~~PUE (0.61 g m^{-2} mm^{-1}). These ~~PUE~~ observations suggest~~s~~ that ~~both elevated CO_2 and elevated temperature~~all treatments had a strong effect on the PUE of the grassland ecosystem~~s~~. ~~However, PUE in~~ In ~~dry~~ the drought year 2018, however, ~~was for~~PUE of C2T0 ~~treatment~~ was much larger than those of C0T2 ~~or~~ and C2T2~~,~~. This~~which~~ might be ~~in addition to~~a result of ~~the~~ a CO_2 fertilization effect ~~for~~ yielding higher AGB at C2T0 as compared to the other treatments under the drought conditions of 2018.~~, benefit from the higher NRW formation. The formation of NRW is beneficial for plants and their biomass production, because NRW can be either directly taken up by plants (Berry et al., 2019) or indirectly improve their growth conditions (Dawson and Goldsmith, 2018) by e.g. reducing leaf temperature, increasing the albedo, and decrease the vapour pressure deficit (Gerlein-Safdi et al., 2018).~~

Results from the observational approach showed different patterns under warmer and drier climate conditions. The PUE at C0CL2 was on average 45 % higher than ~~under~~ at C0CL0. Nevertheless, Figure ~~3~~ 4 B show~~ed~~s also a clear decline of PUE at C0CL2 from 2015 (1.37 g m^{-2} mm^{-1}) to 2018 (0.8 g m^{-2} mm^{-1}), which is accompanied by a decrease of P and NRW by 31 and 22 %, respectively~~, at the site~~. ~~A similar relationship between the decrease in PUE and the decrease in annual P was found by Jia et al. (2015) for temperate grassland in the loess plateau of China. The lower response of PUE~~ at C0CL0 appears ~~to~~ to be less sensitive to changes ~~a decline in the annual P and NRW (Fig. 3; Table S 3 and S 4) of C0CL0 might be related to the wetter conditions at RO than at SE.~~

~~The response of the grassland ecosystem from C0CL0 to changing P and NRW is larger in comparison to responses of C0T0 to atmospheric CO_2 or surface temperature from the manipulative approach. The elevated warming affects the leaf to air vapour pressure deficit at SE and at the treatments with an elevated temperature at GS. Thus, when the temperature of the leaf surface is above that of the air, the gradient of the vapour pressure will also increase and enhance foliar uptake of water in case of wet leaves (Berry et al., 2019).~~

The QP ratio obtained for both approaches (Fig. ~~3~~ 4 C and D) shows~~ed~~ ~~a clear~~ declines if the grassland ecosystem was exposed to warming (i.e. C0T2 and C0CL2). ~~An e~~Elevated CO_2 increased the QP ratio;~~,~~ ~~as the values were~~ on average the values were 21 % higher than for the reference C0T0. However, the most drastic changes in the QP ratio were visible ~~from~~ in the observational approach where QP changed on average by 81 % due to the transfer to a warmer and drier climate (Fig. ~~3~~ 4 D).

The increase of the QP ratio observed for C0CL2 in 2018 ~~in comparison~~relative to the ~~other~~ previous years is related to the large amounts of P during the autumn and winter months of 2017 (see also section 3.1.3).

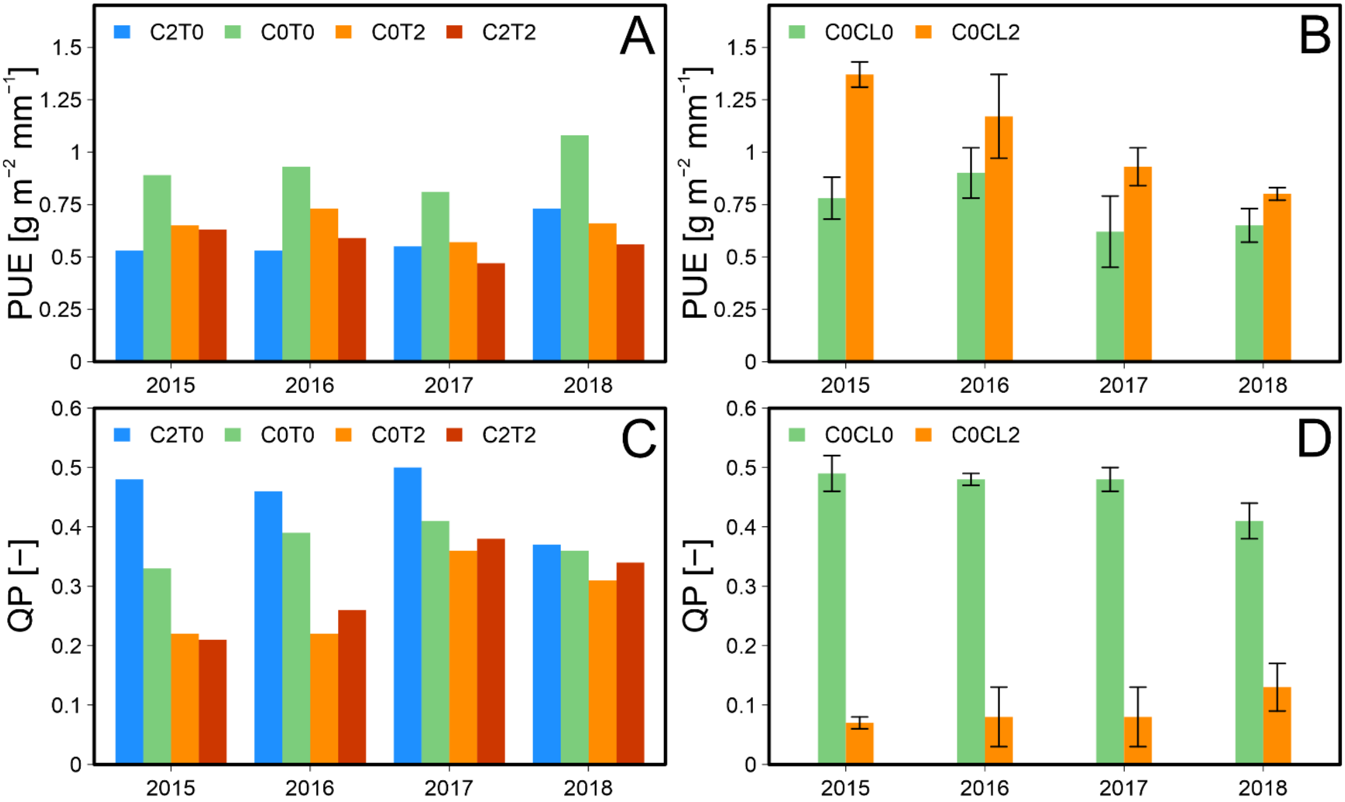

Figure 4~~3~~: Precipitation use efficiency (PUE) during the observational periods 2015-2018 for the manipulative approach Lysi-T-FACE (C2T0; C0T0; C0T2; C2T2) (A) and observational approach TERENO-SOILCan (Rollesbroich C0CL0; Selhausen C0CL2) (B) as well as seepage ~~water~~ to precipitation and NRW ratio QP (-) for the manipulative (C) and observational approach (D).

3.2.3 Relationship between hydroclimatological and ecohydrological indicators

The ecosystem productivity (i.e. AGB), in general, increased ~~in general~~ with ~~the~~ GSP and growing season NRW (Fig. ~~4~~ 5 A)~~,~~. ~~and t~~Thus, the response of ~~the~~ ecosystem productivity ~~in terms of AGB on~~to P and NRW~~)~~ ~~GSP has~~ follows~~a~~ similar patterns ~~in the distribution between~~in the manipulative and the observational approach. However, only ~~the relationships from~~for the observational approach the relationships were found to be significant ($p < 0.01$).~~, which suggests the existent of trade-offs under different P (Wang et al., 2019) and NRW conditions.~~ ET$_a$ in the growing season also increased with increasing GSP and growing season NRW for both approaches, but this relationship was ~~only~~ statistically significant only for the ~~grassland of the~~ observational approach (Fig. ~~4~~ 5 B). ~~The low inter-annual variability in growing season ET$_a$ between years with contrasting GSP, e.g. average reduction of the GSP by 32 % from 2017 to 2018, indicate that water availability is not the limiting factor~~

~~for ET$_a$ at the alpine site. Our results agree well with a previous study by Wieser et al. (2008), which showed for 16 sites across different altitudes (580 and 2550 m a.s.l.) that grassland ecosystems in the Austrian Alps seem not to suffer from water stress even in drier years. In contrast,~~ ET$_a$ showed particularly strong correlation with GSP and growing season NRW for C0CL2 from the observational approach ~~showed, especially for the drier and warmer site (C0CL2) with an~~(adjusted R^2 of 0.9)~~, a strong correlation link between ET$_a$ and P and NRW during the growing season~~. The relationship between ET$_a$ and ET$_0$ during the growing season we~~re~~as significant and found to be negative for the observational approach, but~~and~~ positive for the manipulative approach (Fig. 5 C). ~~The reason for the different response of the grassland can be explained by the site conditions, as ET$_a$ of the alpine grasslands increased and the ET$_a$ of the low mountain range grasslands decreased with larger ET$_0$ during the growing season (Figure 4 C).~~ The relationship between AGB and AI of the observational approach indicates a decrease in ecosystem productivity with increasing aridity under water- and energy-limited conditions. Yet, ~~were similar for the observational approach and AGB increased significantly with smaller AI values, w~~when the water ~~limiting~~ limitation~~conditions~~ diminishes according to the Budyko framework (AI<1), the correlation between AGB and AI weakens (i.e. C0CL0) or disappears (i.e. GS, see Fig. ~~4~~ 5 D~~);~~). Thus,~~but~~ for the manipulative approach, no clear changes of AGB with changing AI were visible because of ~~its~~ the relatively wet conditions (low AI). The relationships between WUE and AI ~~achieved~~ are similar ~~patterns as~~to those shown before for AGB and AI (Fig. ~~4~~ 5 E). The relationships between the PUE and AI (Fig. 5 F) in the observational approach show that the PUE of the grassland ecosystem adapts to increasing water limitation. No relationships from the manipulative climate change experiment were significant, as inter-annual variability of climate conditions (wet and dry) were relatively well buffered ~~due to~~ by the soil water storage, and the hydrological status of the alpine site generally is energy-limited rather than water-limited ~~the large availability of water~~. Nevertheless, the dependencies of AGB, WUE, and PUE on AI found in the manipulative approach appear to be similar to those at the energy-limited site (C0CL0) of the observational approach.~~The AGB and WUE of the grassland-ecosystem from the observational approach declines significantly with an increasing AI. , which suggests that AI can be used as proxy for the site-specific water availability conditions. In contrast, the alpine grassland showed hardly any change in the above-mentioned variables on AI. Our results suggest that ecosystem services (e.g. water, yield) of grasslands could differently benefit or suffer from changing climate conditions. The relationships between the PUE and AI (Fig. 4 F) show that at least for the observational approach, the PUE of grassland ecosystems adapts to conditions with an increasingly water limitationed water availability.~~

~~Altogether, relationships between the AI and AGB and other indicators (WUE and PUE) were different when the grassland ecosystem was energy-limited (GS and RO) or water-limited (SE). The different treatments of the manipulative approach at GS did not lead to large shifts in these relationships. More intense changes in the climatic conditions e.g. using rain shelter might be useful for the manipulative approach to further increase the difference in boundary conditions between treatments and thus better capture the response of the ecosystem on future climate change. However, results for the observational approach demonstrate a significant shift (C0CL0 R^2 < C0CL2 R^2) in the grassland-ecosystem response under climate conditions with a more pronounced water limitation. However, changes in the soil properties after abrupt changes due to organic matter~~

~~decomposition and soil structural changes may have additional effects (Robinson et al., 2016). This highlights that climate change experiments should include sufficiently extreme conditions to better resolve the key question: "How changes in the climate regime will affect and alter the ecosystem function in the future?" (Knapp et al., 2018), because modelling the ecosystem response to changes e.g. like P is of crucial importance to predict future carbon and water cycle (Paschalis et al., 2020).~~

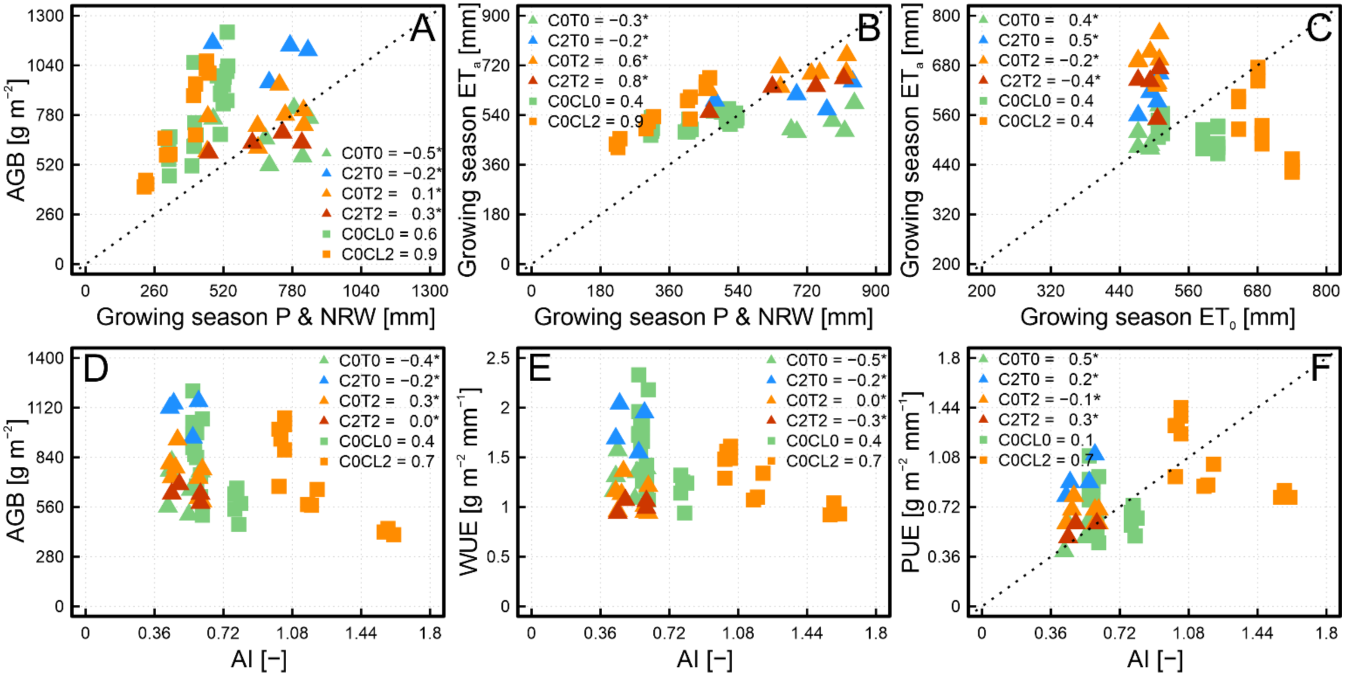

Figure ~~5~~4: Scatterplots of above~~-~~ground biomass (AGB) to growing season precipitation (P) and non-rainfall water (NRW; A); growing season evapotranspiration (ET_a) to growing season P and NRW (B); growing season ET_a to growing season grass-reference evapotranspiration (ET_0; C); AGB to aridity index (AI; D); water use efficiency (WUE) to AI (E); and precipitation use efficiency (PUE) to AI (F). In each subplot variables are shown for all treatments from the manipulative (Lysi-T-FACE C2T0; C0T0; C0T2; and C2T2) and observational climate change approaches (TERENO-SOILCan Rollesbroich C0CL0; Selhausen C0CL2) for the period 2015 to 2018. The adjusted R^2 values for each soil ecosystem are given in the legend and * means that the linear relationship was not statistically significant (p-value > 0.05).

4. Discussion

4.1 Response of water fluxes to climatic changes

The quantitative contribution of NRW to the soil water balance is of ecological relevance (e.g. by foliar water uptake Dawson and Goldsmith, 2018) and can become important for crop production, especially under water-limiting conditions. This is demonstrated by the impact of the extreme weather conditions in 2018, which were associated with a decrease in Northern European crop production (i.e. drought, heat wave; Beillouin et al., 2020). The results from both experimental approaches show that the amount of NRW formed in the non-growing season is higher than that of the growing season. This agrees well with previous findings on the seasonality of dew formation across different climate zones (Zhang et al., 2019; Groh et al., 2019; Atashi et al., 2019). The results from the treatments with elevated temperature demonstrate an impact of warming on the incoming atmospheric water, i.e. NRW and P. Under these treatments, the amount of water reaching the soil ecosystem in the growing season decreases by up to 4 % for P and by up to 24 % for NRW. The observed decrease in NRW agrees well with Feng et al. (2021), who showed that heating with an infrared heater system reduced dew formation for an alpine grassland ecosystem of the Tibetan Plateau by up to 91 %. Surprisingly not only warming but also elevated CO_2 was found to alter the amount of NRW. One possible reason for the observed increase in NRW might be related to the plants itself~~that an increasing latent heat flux due to the airflow above the canopy during the CO_2 application reduces the canopy temperature, increases the temperature gradient between canopy and air, thus enhancing dew formation~~. It is frequently assumed that an increase in atmospheric CO_2 concentration leads to a decrease in stomatal conductivity, which increases leaf temperature (less evaporative cooling; Kirschbaum and McMillan, 2018) but simulation at the leaf level showed that leaf temperature is far more affected by leaf size or wind speed than by indirect effects of elevated atmospheric CO_2 (Konrad et al., 2021). However, effects might be more complex since a recent investigation by Habermann et al. (2019) demonstrated a clear impact of elevated atmospheric CO_2 on the leaf anatomy and physiology of the C4 forage species *Panicum maximum*. Thus, also anatomical and physiological changes of the plant leaves might be an possible explanation of higher dew amounts, because surface properties (i.e. radiative and wetting) are of crucial importance for the formation of dew and dew yield (Trosseille et al., 2021).

As mentioned above, both experimental approaches~~s~~ show that the formation of NRW declines if temperature increases. This agrees well with Tomaszkiewicz et al. (2016), who predicted a decline in dew formation for forecasted trends of increasing temperature and relative humidity under future climatic scenarios for the Mediterranean region. As opposed to the changes in absolute values of NRW, the percentage of NRW relative to P was found to be lower only under the elevated temperature~~s~~ of the manipulative approach, whereas this percentage increased under the warmer conditions in the observational approach. This is related to an important difference of the two approaches, namely the controlled change of individual factors in the manipulative experiment as opposed to the concurrent change of multiple drivers in the observational approach. More specifically, in the observational approach, the site with elevated temperature receives less P than the higher elevated, colder site. Thus, the relative contribution of NRW appears to be more affected by the changes in P than by the effect of warming.

A direct comparison of effects resulting from changes in P in the two experiments is difficult, because only the observational approach includes explicitly a change of P within its design. Including a change of P, especially during the growing season, is important for climate change studies, as the inter-annual variability of the ecosystem productivity (i.e. AGB) at least under water-limited conditions is strongly correlated (Knapp et al., 2018). Hence, climate change experiments that contain information on key interacting variables such as P are indispensable to provide observations that enable a more mechanistic understanding of the ecosystem response (Hanson and Walker, 2020). The manipulative experiment shows relatively low inter-annual variability of AGB (Fig. 3 A), although the observation period includes the drought of the year 2018. According to the Budyko -framework, the hydrological status at the experimental site was energy-limited even in 2018 (Fig. 2). Thus, the inter-annual changes in P were not sufficiently strong to cause a shift to water-limited conditions. Assessing impacts of water stress at the site of the manipulative experiment thus requires including P as an additional treatment in the experimental design. Despite no active control on P within the manipulative approach, treatments with an increased surface temperature affected not only the formation of NRW but to some extent also the amount of P. Apparently, the effect of local warming on the relative humidity of the air within and above the canopy plays a role here. The local decrease of relative humidity might enable some ET_a during P events, thus violating the assumption of zero ET_a during rainfall, underlying the analysis of the lysimeter data. Such local effects on NRW and P in manipulative climate change experiments need further investigation, as they may lead to an under- or overestimation of ecosystem responses.

For ET_a, treatments at GS with an elevated CO_2 and increased temperature resulted in contrasting impacts due to their opposite individual effects on transpiration (Sorokin et al., 2017). Plants respond to elevated atmospheric CO_2 concentrations with a reduced stomatal opening and an increase in photosynthesis (Kruijt et al., 2008; Ainsworth and Rogers, 2007). This is expected to lead to lower ET_a and higher AGB and thus an enhanced plant WUE (Hovenden et al., 2017) compared to other treatments. Our results confirm the water saving effect of CO_2, whereas an effect on AGB was not observed.

In contrast to elevated CO_2, elevated temperatures lead to an increase in the vapour pressure deficit and thus enhanced evapotranspiration (Kirschbaum and McMillan, 2018). Kirschbaum and McMillan (2018) suggested for a range of locations from tropical to boreal forest that the transpiration-depressing effect of elevated CO_2 was stronger than the opposite effect of elevated temperatures. Lenka et al. (2020) showed that treatments with an elevated CO_2 concentration as well as combined increase of CO_2 and temperature reduced the stomatal conductance, lowered the ET_a, and consequently improved WUE of soybeans. In our experiments, ET_a of C2T2 was higher compared to reference, but clearly below values of ET_a from C0T2. This suggests that the effect of elevated CO_2 to reduce ET_a only partially compensated for the effect of elevated temperature in the combined C2T2 treatment.

Kirschbaum (2004) suggested that the effect of CO_2 on ET_a is more pronounced for C3 plants under water--limited conditions and at higher temperatures (Kirschbaum, 2004), because it enhances the WUE of the plant (Kirschbaum and McMillan, 2018). However, its effect under non-water--limited but temperature limited growth conditions on plants is still unclear. The low ET_a of the treatment C2T0 during the dry year 2018 indicates that elevated CO_2 can mitigate effects of summer droughts on alpine grasslands, which agrees well with Inauen et al. (2013). They showed that elevated CO_2 reduced ET_a by up to 7 % across a range of different grassland types in the central Swiss Alps.

Interestingly, the ET_a response to the drought conditions in 2018 differed between the manipulative and observational approach. In the manipulative experiment, ET_a was found to be mainly energy-limited (Fig. 2) and thus increased under conditions with elevated temperatures (Fig. 1 J). In contrast, the observational approach showed a clear decrease in ET_a under conditions with elevated temperatures, as the soil ecosystem was shifted from an energy-limited to a water-limited regime

(Fig. 2) due to the transfer from RO to SE (Rahmati et al., 2020). A similar reduction of ET_a across different ecosystem types was observed for sites in Europe affected by the drought in 2018 (i.e. forests, grasslands, croplands and peatlands; Graf et al., 2020). Our results reveal that the limitation of the water supply at site SE increased during the drought and the heat wave intensified the water stress (AI in 2018 ≥ 1.6) and thus significantly reduced grassland ET_a.

The above discussion shows that the manipulative experiment mainly provides insights into effects of climatic changes under energy-limited conditions, whereas the observational approach enables investigations under both energy-limited and water-limited conditions. Despite this advantage in the design of the observational approach, the influence of elevated atmospheric CO_2 on the ET_a response of the soil ecosystem is missing, which is an important aspect for assessment of future climate change impacts.

Another question was how climatic changes affected the drainage behaviour (NetQ) and water storage of the soil ecosystems. In the manipulative approach, elevated CO_2 resulted in a significant increase in NetQ, whereas elevated temperatures (C0T2 and C2T2) significantly reduced NetQ. Ultimately, this is a result of the above-described changes in grassland ET_a, which agrees well with findings from Mastrotheodoros et al. (2020) for the European Alps. Previous investigation for a grassland at the Swiss Alps showed only a slight increase of seepage under elevated atmospheric CO_2 (Inauen et al., 2013). These changes in seasonal seepage potentially affect the catchment runoff, which is important for hydropower productivity and profitability in Alpine regions (Anghileri et al., 2018).

The observational approach also showed the tendency for NetQ to decrease under elevated temperature, but in a much more pronounced way and for different reasons. At water-limited site SE, the non-growing season P is mainly used to replenish the large decrease in ΔS observed during the growing season. This partly explains the low impact of the dry year 2018 on NetQ at water-limited site SE. However, for the energy-limited ecosystem a strong decline in growing season NetQ (159 %) was observed in 2018 compared to the average 2015 to 2017, which eventually is expected to affect stream flow. Although stream flows are buffered by groundwater, reduced recharge will deplete regional water storage reserves as shown by Fennell et al. (2020) for a catchment in 2018 in Scotland. Long-lasting droughts can affect the soil water storage even in the following year, if winter P is not sufficient to fully replenish the depleted soil water storage (Riedel and Weber, 2020). The decrease of NetQ underlines that the physical and biological response to changing climatic conditions as well as the hydrological status of the ecosystem control water fluxes. Warming of land surface, reduced P, increased atmospheric concentrations of CO_2 and higher atmospheric demand for evaporation reduce seepage and thus groundwater replenishment.

4.2 Climate change impact on biomass production and ecohydrological indicators

The partially sharp decline in AGB production under changing climatic conditions observed in both experimental approaches can be attributed to very distinct reasons. The AGB decrease for the manipulative approach might be related to an increase of heat stress due to the treatments, which is either directly induced by an elevated canopy temperature or in case of elevated CO_2

indirectly, because elevated CO_2 probably reduces evaporative cooling of plants (Obermeier et al., 2018). The results are in contrast to the widely expected positive effects of increasing CO_2 on productivity of agricultural land (Amthor, 2001; Degener, 2015; Zheng et al., 2018). The positive effect of CO_2 fertilization on AGB was only visible for the treatment C2T0 under the conditions with less P and higher temperatures in the year 2018. This agrees well with previous studies (see e.g. Morgan et al., 2004; Ainsworth and Rogers, 2007). In addition, the vegetation composition might have changed between treatments and reference, as drought and heat induced shifts at the community and plant functional group level impact AGB production of alpine grasslands (Tello-García et al., 2020).

The decline of AGB under a drier and warmer climate of C0CL2 in the observational approach is closely related to the hydrological status of the soil ecosystem. The combination of lower incoming atmospheric water (i.e. P and NRW) coupled with higher evaporative demand and a longer growing season results in greater pressure on the soil water resources under water-limited than under energy-limited conditions. The AGB for C0CL2 was reduced during heatwaves in 2016 and 2018. In the summer 2018, the soil ecosystem was exposed to an increasing drought intensity and the plants turned slightly dry and brown and were visibly affected by drought stress (Rahmati et al., 2020).

In 2015, the AGB of C0CL2 was higher than that of C0CL0, which differs from the others years. This might be related to a moderate drought in 2015 (Ionita et al., 2016) combined with higher temperatures and solar radiation. For the first and most important cut in the season, C0CL0 achieved a below-average biomass, which can be explained by the exceptional dry conditions in May in this region (i.e. second driest month since 1950; Ionita et al., 2016). The soil ecosystem C0CL2 in SE, however, was less affected by this drought, as biomass production was able to develop much earlier in this season. The year 2015 had the longest growing season (250 days) in SE and the warm conditions before the drought in May and a sufficient water availability after winter led to similar AGB as in 2016. However, also here a change in plant community composition might be the reason for the altered AGB production. Observations on the species abundance from the observational approach underlines this explanation, as the plant community of the transferred soil ecosystem changed under water-limited conditions, by reducing the abundance of herbs on cost of grass species (Jarvis et al., 2021). Ecohydrological simulation of the grassland at RO and SE by Jarvis et al. (2021) for the years 2013 to 2018 suggests that the plant community adapted to the changing climate conditions in SE by developing a deeper root system, with a greater proportion of assimilates being distributed below ground, while stomatal conductance also increased significantly. These results show the importance of the interplay between environmental conditions (i.e. temperature) and the seasonal development of the plants (e.g. duration of the vegetation period), which cannot be taken into account in the treatments of the manipulative approach and thus represents a further limitation.

As expected, the different treatments also affected the WUE of the alpine grassland. Among the different treatments C2T0 achieved the highest WUE. It was also shown previously for a range of different agricultural ecosystems (Nendel et al., 2009; Roy et al., 2016) that WUE increases, as plants increase their assimilation rates and simultaneously reduce their water loss by decreasing stomatal conductance under elevated CO_2 (Lammertsma et al., 2011). A higher temperature, however, seems to increase the “non-productive” water losses, as evident from treatment C0T2 or C2T2, which led to less efficient crop water use as compared to the unheated plots (Fig. 3 C). The small difference between WUE of C0T2 and C2T2 suggests that the higher temperatures dominated the response of the grassland ecosystem under conditions with elevated temperature and atmospheric CO_2 concentration (no compensation). The largest difference in WUE between C2T2 and C0T0 was seen in 2016 and 2018. This might be related to increasing heat stress under treatment (Obermeier et al., 2018).

Similar to manipulative approach, the observational approach showed lower WUE under elevated temperature. De Boeck et al. (2006) also showed that warming of several grasslands in Belgium led to decrease of biomass production and WUE. But the same study also implies that WUE of individual species was affected differently by warming, which might have led to compositional changes in the ecosystem. One reason for lower WUE under elevated temperature and/or water-limited conditions might the divergent biomass partitioning to above and below ground in grasslands. Experimental studies found that frequent soil drying and droughts enhance root growth and the production of below-ground biomass production (e.g. Hofer et al., 2017; Nosalewicz et al., 2018; Padilla et al., 2013). At least for the observational approach, simulation of crop growth and water fluxes with an eco-hydrological model reveals a deeper root growth (i.e. more below ground biomass) under drier climatic conditions at SE (Jarvis et al., 2021).

Comparing the results of WUE and AGB between both approaches suggests that the impact of drought in 2018 on the WUE and AGB under ambient conditions was much larger in the lowlands than at higher altitudes. Both approaches showed a decline in AGB and WUE under dry conditions. In addition to possible plant compositional changes, an elevated heat stress might further explain the different response to AGB and WUE within the manipulative experiment, whereby for the observational approach additional water stress due low GSP and a more depleted soil water storage was the main driver for changes in AGB and WUE.

The PUE values obtained are within the range (0.05 to 1.81 g m^{-2} mm^{-1}) reported by Le Houérou et al. (1988) and Jia et al. (2015). The observed effect of elevated temperature on PUE was different among the approaches. The water-limited soil ecosystem C0CL2 consumed nearly all incoming atmospheric water (i.e. P and NRW) for plant growth and drastically reduced drainage (average $QP < 0.1$), whereas at energy-limited ecosystem water was not limiting plant productivity (range QP:0.2 to 0.5). Our results further suggest that the formation of NRW should be part of PUE calculations, as under dry conditions water from dew or fog might be beneficial for plants and their biomass production. NRW can be either directly taken up by plants (Berry et al., 2019) or indirectly improve their growth conditions (Dawson and Goldsmith, 2018) by e.g. reducing leaf temperature, increasing the albedo, and decreasinge the vapour pressure deficit (Gerlein-Safdi et al., 2018).

4.3 Climate change impact on functional relationships

The observational approach demonstrates a clear pattern in functional relationships. Decreasing incoming atmospheric water during the growing season (P and NRW) significantly reduced biomass productivity of the grassland, which is consistent with other studies (Zhang et al., 2020; Hossain and Beierkuhnlein, 2018; Bernhardt-Römermann et al., 2011). Our results are in contrast to findings of Knapp et al. (2018), as the slope of the relationship between AGB and the incoming atmospheric water in the growing season was stepper in the observational compared to the manipulative approach (Fig. 5 A). The lower sensitivity of AGB to P and NRW in the manipulative approach suggests that under non-water-limited conditions other climatic variables, such as temperature, or additional factors, such as the frequency of disturbance and fertilisation, may be more important for AGB productivity (Bradford et al., 2006). This is consistent with the low inter-annual variability in growing season ET_a. Even between years with contrasting P and NRW (e.g. average reduction by 23 % from 2017 to 2018), ET_a was only slightly reduced (e.g. average reduction by 9 % from 2017 to 2018). Thus, water availability generally is not the limiting factor for ET_a at the alpine site, although water stress may occur temporarily under drought. Our results agree well with a previous study by Wieser et al. (2008), which showed for 16 sites across different altitudes (580 and 2550 m a.s.l.) that grassland ecosystems in the Austrian Alps seem not to suffer from water stress even in drier years.

The functional relationship of AGB, WUE or PUE with AI also reflect the importance of the hydrological status (i.e. water limitation) on ecosystem productivity and efficiency. These functional relationships were significantly negative under the water-limited conditions of the observational approach, i.e. increasing aridity caused decreases in these indicators. A negative significant relationship also found for the energy-limited soil ecosystem (C0CL0) is mainly related to the exceptionally dry year 2018. In other years, AGB and WUE varied considerably at the energy-limited sites both in the observational and the manipulative approach, while AI did not change (Fig. 5 D, E, and F).

The analysis of the functional relationships between hydroclimatological and ecohydrological indicators reveals that climate change experiments need to include sufficiently extreme conditions to resolve the key question: “How changes in the climate regime will affect and alter the ecosystem function in the future?” (Knapp et al., 2018). Ecosystem responses to changes in P are of crucial importance to assess future changes in the carbon and water cycle (Paschalis et al., 2020). More distinct changes in the P conditions, e.g. by using rain shelter, in the manipulative approach thus would allow to better capture the response of the ecosystem to future climate change.

5. Conclusions

A manipulative and an observational lysimeter-based approach was used to assess~~ing~~ the climate change impacts on the water balance and productivity of a low mountain and alpine grassland ecosystem. ~~grassland soil ecosystem were analysed and compared over a period of four years, including the exceptionally dry year 2018. The aim was to quantify the effect of changing climatic conditions on the water cycle and productivity of grassland ecosystems by the use of high precision lysimeter data. The main hypothesis was that the response of the grassland ecosystems on changing climatic conditions will differ among the two distinct experimental approaches.~~

Both approaches~~Results of the comparisons between grassland ecosystems from two different climate change approaches~~ showed that elevated temperature increases actual evapotranspiration (ET_a) and decreases aboveground biomass (AGB) of grassland ecosystems but has the opposite effect on ET_a under drought conditions. This is most evident from results of the observational approach, but also found in the manipulative experiment during exceptionally dry periods in 2018. ~~suggest that the most critical factor was the water availability.~~ The incoming amount of atmospheric water (i.e. ~~P~~precipitation (P) and non-rainfall water (NRW)) ~~amount~~ and temporal variability of the events thus played a major role i~~o~~n the response of the ecosystem~~to future climate,~~ but responses in terms of the water balance and biomass production ~~are~~ were partially buffered by the soil. ~~i.e. that water or heat stress can be mitigated by the status of ecosystem conditions. Thus, climate change experiments that contain information how altered P and NRW patterns and droughts affect ecosystem response (i.e. actual evapotranspiration ET$_a$, above ground biomass AGB) would be helpful to further understand how ecosystems will react under soil conditions with less plant-available water. Results from~~ T~~he manipulative climate change approach (indicating that both~~ In the manipulative approach, both elevated temperature and elevated CO$_2$ concentration altered P and NRW, suggesting that effects of the experimental conditions on NRW and P need to be considered ~~in global change experiments~~ to avoid an over- (elevated temperature) or underestimation (elevated CO$_2$) of the effects ~~of climate change~~ on ecosystems response, especially for sites where water limitation plays a role. E~~The e~~levated temperature was the dominant factor for changes in~~g~~ ET$_a$ ~~of the grassland ecosystem~~ under the non-water-~~-~~limited ~~but temperature limited growth~~ conditions of the manipulative experiment.~~,~~ E~~as effect of e~~levated CO$_2$ concentration only partially ~~on ET$_a$ was largely~~ compensated the effect of ~~by~~ higher temperatures (increasing ET$_a$) within the combined treatment. However, the water-saving effect of elevated CO$_2$ gained importance under drought conditions. ~~Future climate change experiments should account for these effects and thus should include elevated CO$_2$ concentrations, especially under drier environmental conditions or droughts where such a compensation is most decisive, because water and heat stress for plants significantly affects productivity (e.g. AGB) and the water use efficiency (WUE) of grassland ecosystem~~.

The imposed changes in the climatic conditions resulted in a modification of the seasonal patterns of seepage and thus affects groundwater recharge in~~from~~ both experimental approaches. ~~depends on the response of plant and soil (ET$_a$) to changing climatic conditions, suggesting that changes affecting water fluxes from the land surface will play a crucial role to predict future ecosystem water balances.~~ The effects of drought on drainage~~seepage water~~ and soil water storage ~~that potentially leading to groundwater recharge~~ were more pronounced at sites under wetter (i.e. energy-limited) soil conditions, because here the higher demand for evapotranspiration could~~an~~ be satisfied at~~on~~ the expense of a decreasing soil water storage. Under water-limited conditions, seepage was found to depend strongly on the replenishment of the soil-water storage during the non-growing season.

~~The response of AGB and WUE on altered climatic conditions from the manipulative and the observational approach suggests that changes in boundary conditions (i.e. P, elevated CO$_2$ or temperature) affects both variables in temperate humid grassland ecosystem in a similar way.~~

Indicators such as aridity index and its relationship to~~ biomass~~ ecosystem productivity~~on~~ (AGB) and efficiency (i.e. water and precipitation use efficiency) differed between the two approaches. ~~plant water use revealed that~~ It was found that ~~the status of the grassland ecosystem is important (i.e.,~~distinguishing between~~temperature,~~ energy-limited and~~, or~~ water-~~-~~limited~~)~~ conditions is important to understand the response of the ecosystem to changing climatic conditions. Water-limited ecosystems show distinct relationships between hydrological and ecological indicators. In contrast, ecological indicators may vary considerably in energy-limited systems even if hydrological indicators remain nearly constant. ~~The inter-annual variability of climatic conditions in the context of climate change experiments was found crucially important for the water budget and the connected aboveground biomass production, since the more different the conditions, the clearer the effects, including the occurrence of temperature or water stress, the grassland ecosystem seems to show a clear response.~~

~~The results of this study confirmed confirms that ecosystem response of both climate change approaches, depend mainly on the ecosystems' status with respect to temperature and energy or water limitation. The larger impact of drought on biomass production in wetter climates suggests that ecosystems may adapt upon conditions during drought period.~~ The responses of soil water fluxes and biomass production strongly depend on the ecosystems' status with respect to energy or water limitation. In the present study, only the observational approach covered both of these conditions, confirming our hypothesis about the different ecosystem response to changing climatic conditions between the approaches. Yet, only the manipulative approach included elevated CO_2. ~~Thus,~~It was found that manipulative and observational approaches~~d~~ ~~were found to~~ complement ~~one~~ each other~~another~~, but that it is~~requires~~ important to consider both the general state~~us~~ of the ecosystem ~~as well as~~and the occurrence of extreme conditions in the approaches. Future studies should integrate all factors (precipitation, temperature and CO_2) from the manipulative and the observational approach in order to obtain a complete ecosystem response and better understanding of tipping points in ecosystems, which may help improving model predictions of how changes in climate regimes will affect the function of ecosystems.

Data availability

All data for the specific lysimeter and weather station (raw data) can be freely obtained from the TERENO data portal (https://teodoor.icg.kfa-juelich.de/ddp/index.jsp (last access: 9 February 2021; Kunkel et al., 2013), lysimeter station Rollesbroich and Selhausen: RO_Y_01 and SE_Y_02). The processed data to support the findings of this study can be acquired upon request from Jannis Groh. The raw data for the lysimeter and weather station can be obtained upon request from Markus Herndl.

Author contribution

MH and TP conceived the experiments at the corresponding site in Austria and Germany. JG and VF had the idea and designed the study. MH and JG provided the data for the corresponding lysimeter stations. VF and JG performed the data analysis, and reviewed and wrote the manuscript with equal contributions from all co-authors.

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Competing interests

The authors declare that they have no conflict of interests.

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