ClimGrassHydro - Ecohydrology of mountain grasslands under global change: mechanisms and consequences

Final project report

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Deutsche Kurzfassung

Der globale Wandel, insbesondere die Freisetzung von Treibhausgasen wie CO_2 in die Atmosphäre, führt zu einer fortschreitenden Erwärmung der Erde und dabei auch zu einem vermehrten Auftreten von extremen Dürreereignissen. Das ÖAW-ESS-Projekt ClimGrassHydro hatte zum Ziel, die individuellen und kombinierten Auswirkungen von Erwärmung, erhöhtem CO_2-Gehalt und Sommerdürre auf die Produktivität und Wassernutzung von bewirtschaftetem montanem Grünland zu untersuchen. Grünland spielt in Österreich und vielen Regionen der Welt eine wichtige Rolle für die Landwirtschaft, aber auch für den Wasserhaushalt, die Klimaregulation und die Artenvielfalt. ClimGrassHydro wurde als Beitrag zum Langzeitexperiment ClimGrass in Raumberg-Gumpenstein durchgeführt. Auf insgesamt 54 Grünlandparzellen werden die Auswirkungen von unterschiedlichen atmosphärischen CO_2-Gehalten (aktuell: ca. 420 ppm, sowie eine Erhöhung um 150 bzw. 300 ppm, bezeichnet mit C0, C1 bzw. C2), Lufttemperaturen (aktuelle Umgebungstemperatur, sowie eine Erhöhung um 1,5° bzw. 3°C, bezeichnet mit T0, T1 und T2) und experimentell herbeigeführter Sommerdürre (bezeichnet mit D) untersucht. ClimGrassHydro kombinierte Datenreihen von insgesamt acht Untersuchungsjahren, darunter Ertragserhebungen und Lysimeter-Messreihen, mit detaillierten Messungen von CO_2- und Wasserdampf-Flüssen mit Ökosystemkammern und Membranschläuchen im Bodenprofil sowie gezielten Tracer-Studien mit isotopisch angereichertem Wasser. Darüber hinaus kamen zur Integration und Interpretation der Messdaten eine Reihe von Modellen zum Einsatz, deren Bandbreite von hydrologischen Modellen auf der lokalen und regionalen Skala bis hin zu globalen Ökosystemmodellen reichte.

Während eine experimentelle Erwärmung zu einem Anstieg der Bestandesverdunstung (Evapotranspiration, ET) führte, verringerten erhöhtes CO_2 und vor allem Sommerdürre die ET. Diese Veränderungen der ET waren primär auf einen erhöhten Verdunstungsbedarf bei Erwärmung sowie auf eine verringerte Blattleitfähigkeit für Wasserdampf bei erhöhtem CO_2 und bei Dürre zurückzuführen. Die Dürreeffekte auf den Wasserverbrauch und den Grünlandertrag waren in einem zukünftigen Klimaszenario (C2T2D) deutlich stärker ausgeprägt als unter aktuellen Klimabedingungen (C0T0D). Dürre in einem zukünftigen Klimaszenario (C2T2D) verringerte dabei die Produktivität stärker als die ET (geringere Wassernutzungseffizienz), reduzierte den Anteil der Pflanzentranspiration an der ET und führte zu einer Verlagerung der Wasseraufnahme durch die Wurzeln in tiefere Bodenschichten. Die untersuchten Umweltfaktoren wirkten sich auch auf die hydrologischen Eigenschaften des Bodens aus. Erhöhter CO_2-Gehalt und Erwärmung führten zu einer hydrologischen Trennung zwischen den obersten und den tiefer gelegenen Abschnitten des durchwurzelten Bodens, während die zusätzliche Trockenheit auch die Durchmischung von Niederschlags- und Bodenwasser einschränkte. Mehrere aufeinanderfolgende Jahre von Sommerdürre in einem zukünftigen Klimaszenario (C2T2D) führten dazu, dass der Boden das Niederschlagswasser rascher durch Makroporen weiterleitete und das Wasserspeichervermögen des Bodens verringert war.

Um einen transdisziplinären Austausch und die Integration von Wissen mit Interessenvertretern aus dem Landwirtschafts- und Wassersektor zu entwickeln, wurden zwei breitere Stakeholder-Workshops organisiert, an denen alle vier Projekte des ÖAW-Grundwasser-ESS-Clusters teilnahmen. Darüber hinaus wurde ein Fact Sheet erstellt, das in einer Publikationsreihe des Climate Change Center Austria veröffentlicht wird und das eine Synthese der Auswirkungen von Sommerdürre unter aktuellen und künftigen Klimabedingungen auf bewirtschaftetes Grünland allgemein verständlich zugänglich macht. Das Fact Sheet enthält auch einen Überblick über die wichtigsten Management- und Anpassungsoptionen, die in einem zusätzlichen Stakeholder-Workshop und einer Expertenkonferenz diskutiert und verfeinert wurden. Weiters trug ClimGrassHydro zu einer transdisziplinären internationalen Publikation zur Anpassungsfähigkeit sozial-ökologischer Systeme an Klimaextreme bei.

Abstract

ClimGrassHydro aimed to understand the individual and combined effects of warming, elevated CO_2, and drought on the ecohydrology of mountain grassland. Specifically, we sought to quantify the detailed mechanisms and ecohydrological implications of these global changes on the storage and movement of water through a grassland system. We utilized the long-term climate manipulation experiment ClimGrass in Raumberg-Gumpenstein, which imposes various continuous atmospheric levels of CO_2 (ambient, +150, +300 ppm; denoted by C0, C1 and C2, respectively), air temperature (ambient, +1.5°, +3°C; denoted by T0, T1 and T2), and experimentally induced drought (denoted by "D" and referred to hereafter as "simulated") on managed grassland plots. We used long-term and ongoing hydrological and tracer data from the site to infer how various climate change scenarios can 1) alter the movement and cycling of water through grasslands and 2) understand the implications for grassland plants and water yield.

We consistently found that, while warming generally led to an increase in evapotranspiration (ET) (+3°C; median of +20%), elevated CO_2 (+300 ppm; -5%) and simulated drought conditions had the opposite effect and resulted in a decrease in ET relative to ambient conditions. When we expanded these results to the catchment scale the effects of warming on ET were preserved, but larger precipitation volumes dampened any analogous reductions in subsurface water storage and flow. Inverse modeling of ET suggests that these changes in ET were largely driven by overall reductions in plant stomatal conductance under elevated CO_2 and increased evaporative demand in warming treatments. Plant water use responses to global change were particularly sensitive to warming and CO_2 enrichment under water stress. During naturally occurring dry periods we observed reductions in plant yield across all treatments, with the least impact in plots treated with elevated CO_2. When simulated drought was combined with elevated CO_2 and warming we detected lower water use efficiency (WUE), reductions in the amount of transpiration (T) relative to ET (T/ET), and root water uptake (RWU) from deeper soil layers. Our global change treatments also affected soil hydrological characteristics. Elevated CO_2 and warming produced hydrological disconnections between the shallowest and deepest sections of the root zone, whereas the addition of drought also restricted mixing between incoming precipitation and bulk soil water. Altogether, when exposed to multiple years of warming, elevated CO_2 and summer drought, the studied grassland conserved water use, and soils transmitted water more rapidly through macropores that resist mixing with a soil matrix which holds less effective soil moisture. Thus, overall, ClimGrassHydro provided novel and direct depictions of the ecohydrological repercussions of a changing climate, extending from subsurface flow properties to plant water use and grassland yield. Furthermore, it applied unique observational and experimental datasets to numerically model and project various climate scenarios into the future and across scales.

To develop a platform for transdisciplinary exchange and integration of knowledge with stakeholders from the agricultural and water sectors we organized two broader stakeholder workshops involving all four projects from the ÖAW groundwater ESS-cluster. We produced a Fact Sheet (to be published in the CCCA-series), which provides a broadly accessible synthesis of the effects of drought on managed grassland, accounting for the particular situation in Austria. The fact sheet also includes an overview of major management and adaptation options, which were discussed and refined at an additional stakeholder workshop and an expert conference. Finally, we contributed to an international publication on advancing the understanding of the adaptive capacity of social-ecological systems to absorb climate extremes and related management options.

Introduction

Global change in the Anthropocene will impose various permutations of warming, atmospheric carbon dioxide levels, and moisture availability on terrestrial ecosystems.[1] Assessing the future of water resources requires a mechanistic understanding of how these climatic alterations are manifested in interactions between vegetation and subsurface flow and storage. When considered individually, CO_2 enrichment and warming can have antagonistic effects on the terrestrial water cycle. Higher air temperatures increase atmospheric demand for water which accelerates the rate of evapotranspiration (ET),[2,3] whereas CO_2 enrichment may drive plants to close their stomata,[4] lowering transpiration rates and increasing soil water retention during the growing season.[5,6] The latter effect has the potential to increase runoff and streamflow,[5,7] while the former could increase the frequency of extreme droughts.[8,9] However, the combination of CO_2 enrichment and warming in global scale model ensembles forecasts contrasting scenarios, ranging from >30% decrease in runoff for much of the Northern Hemisphere[1] to a reduction of drought-stressed land area altogether.[6] Climate manipulation experiments (CME) best constrain these model outputs, yet CMEs rarely consider individual and combined effects of climate change[10] (e.g., CO_2, warming, and drought). As Earth's hydrological cycle intensifies[11], the need to directly quantify the ecohydrological impacts of climate change grows.

ET is, however, rising globally (e.g., 0.5-1.5 mm y^{-1} from 1980-2010)[12] alongside increases in soil moisture reduction and drought frequency and severity in many regions. Drought can trigger complex ecohydrological feedbacks: by reducing soil moisture, stomatal conductance—and thus ET—drought favors surface warming that triggers heatwaves, which further enhances drought effects.[13,14] Increased occurrence of droughts alone is believed to have caused a tripling of agricultural losses in Europe from 1964-2015.[15] Thus, explicit knowledge of coupled plant-soil-atmospheric feedback mechanisms under controlled climatic conditions is in high demand. Though rising levels of ET have been attributed namely to increased evaporative demand and greening of vegetation,[12] the ecohydrological responses of plant water use[16] and soil hydraulics[17,18] are poorly constrained. For example, the contribution of the amount of water lost during plant carbon fixation, or water use efficiency (WUE), to observed changes in ET is identified as a key knowledge gap by the Intergovernmental Panel on Climate Change (IPCC).[12] Though, plant hydrological responses to CO_2 enrichment seem to depend on whether a system is energy or water limited.[16] From a soil physical perspective, extreme drying can physically alter the structure of soil material such that flow and storage properties are irreversibly altered.[19-21] These changes can be manifested through crack formation,[20] increases in macroporosity,[21] lowered storage capacity,[18] and greater preferential flow.[22] Alternatively, it has been suggested that CO_2 enrichment may drive increases in root exudation and mycorrhizae activity which convey greater soil aggregate stability[23] and more water retention in finer pores.[24] Likewise, the higher residence time of transient soil water provided by lowered transpiration may buffer the impact of severe droughts.[6] Despite these few documented changes to soil physical properties under isolated effects of climate change, little to no direct evidence exists to suggest that soil physical properties can be altered under combined global change factors. Altogether, the full ecohydrological implications of interactive global change factors remain uncertain.

Project objectives

The overarching objectives of ClimGrassHydro were to:

- understand the individual and combined effects of multiple levels of climate warming, elevated CO_2 and severe drought on the ecohydrology of managed mountain grasslands,
- quantify the implications of ecohydrological responses for agricultural yield and water yield, and
- develop a platform for transdisciplinary exchange and integration of knowledge with climate economics and stakeholders from the agricultural and energy sectors for identifying vulnerabilities and possibilities for climate-smart adaptation.

The ClimGrassHydro approach

ClimGrassHydro was based at the ClimGrass facility in Raumberg-Gumpenstein which imposes various continuous atmospheric levels of CO_2 (ambient, +150, +300 ppm; denoted by C0, C1 and C2, respectively), air temperature (ambient, +1.5°, +3°C; denoted by T0, T1 and T2), and simulated drought (denoted by "D") on managed grassland plots (**Figure 1**). ClimGrassHydro utilized long-term and ongoing hydrological and tracer data from the site to infer how various climate change scenarios can alter the movement and cycling of water through grasslands from vegetation, agricultural yield, and hydrological perspectives (**Figures 1** and **2**). Namely, key hydrological data were derived from weighable large (1.4 m x $1 m^2$) and SmartField lysimeters (SFLs'; 0.6 m x 0.3 m^2), and soil moisture time domain reflectometry (TDR) sensors spanning the field site (**Figure 2**). Core hydrological tracer data include water stable isotope records (^2H and ^{18}O) of precipitation, continuous in situ isotopic monitoring of water within the soil profile via a cavity ringdown spectrometer from vapor-permeable membrane tubes (Picarro, **Figure 2**), canopy chamber measurements of T and bulk ET using a portable Picarro system, and periodic destructive leaf and soil water measurements. We used these datasets to directly quantify ecohydrological responses to climate change, and inverse model, upscale, and project results in the future.

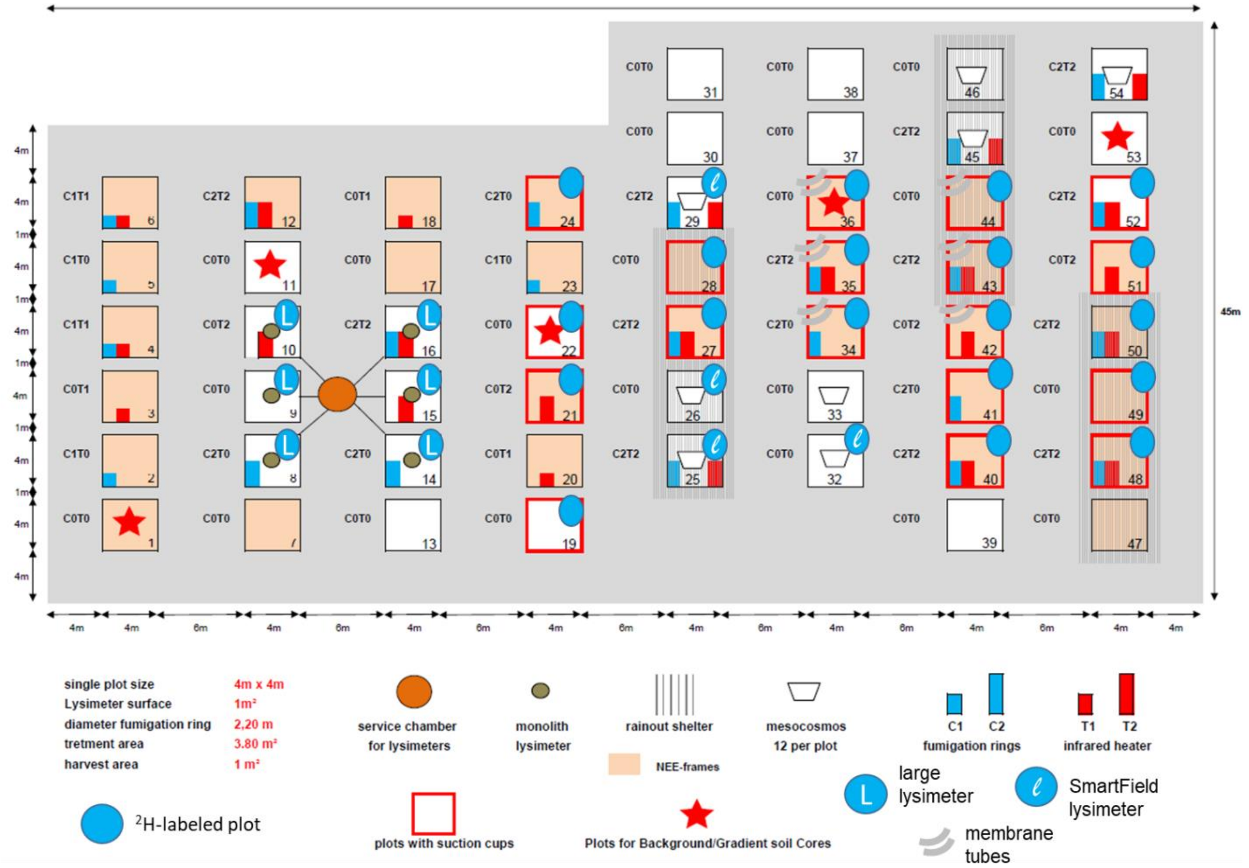

Figure 1. ClimGrass field schematic with relevant plots, treatments, and infrastructure. Treatments contain combinations of elevated atmospheric levels of CO_2 (where ambient, +150, +300 ppm are denoted by C0, C1 and C2) and air temperature (ambient, +1.5°, +3°C; denoted by T0, T1 and T2), and recurring drought simulations (denoted by "D") performed with rainout shelters. "Membrane tubes" corresponds to plots where soil water stable isotope signatures were monitored in situ.

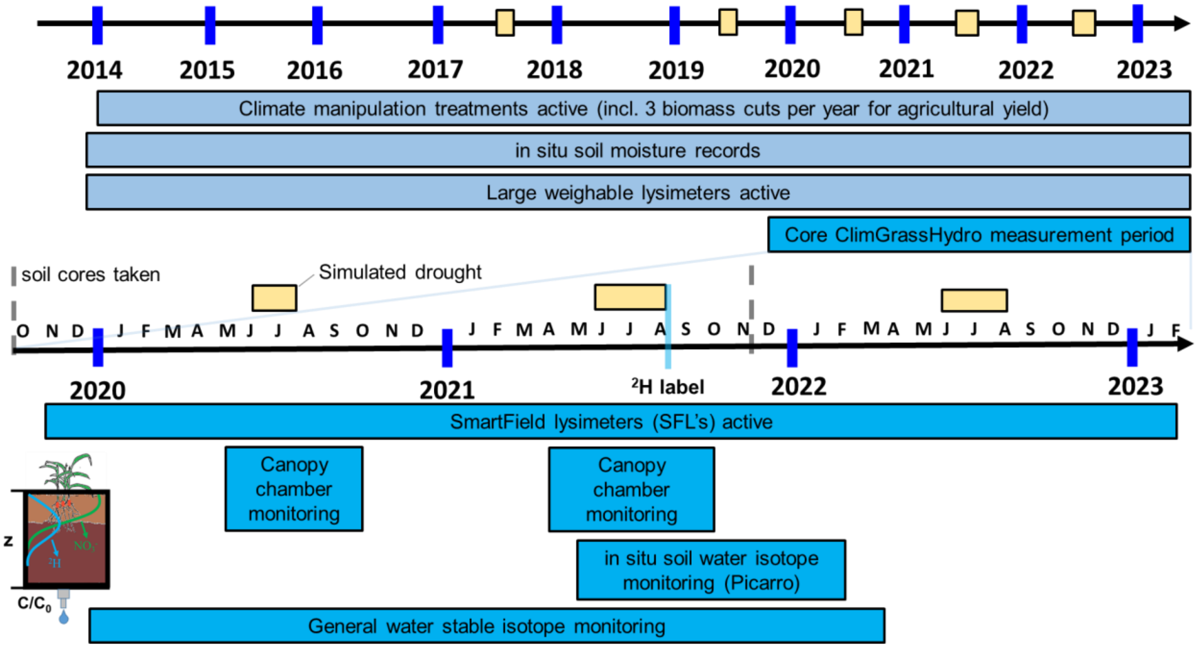

Figure 2. General timeline for relevant ClimGrassHydro analyses. "Soil cores'' tabs designate periods where cores were taken for soil physiochemical and hydraulic property analysis. "Canopy chamber monitoring" tabs denote periods where canopy measurements were conducted to derive carbon and water ecosystem fluxes for water use efficiency and partition transpiration from evapotranspiration using stable isotope records (with Picarro cavity ringdown spectrometer). In situ soil water isotope monitoring was carried out with a Picarro- coupled with a vapor membrane tube sampling system, yielding records from 6 climate manipulation treatments at 4 soil depths every 4 h. "General water stable isotope monitoring" denotes the core period of isotope records, including periodic destructive samples of soil and leaf tissue.

Results of work package 1 (field experiments)

Work package 1 encompasses the core experimental components and primary data sources of the ClimGrassHydro project. Here we use a series of long-term monitoring records and field campaigns to address the first two core objectives. The descriptions below of work packages 1 and 2 are structured as a series of "action" headers followed by key findings.

Warming and elevated CO_2 altered the ***water budget****: elevated CO_2 alone increased seepage and decreased evapotranspiration (ET), while warming, and warming combined with elevated CO_2 did the opposite*

The effects of warming (+3°C) and elevated carbon dioxide (+300 ppm CO_2) on the water budget were multifaceted and additive. While warming generally led to an increase in ET, elevated CO_2 and simulated drought conditions had the opposite effect—a decrease in ET relative to ambient conditions (**Figure 2a** and **2b**). The combination of warming and elevated CO_2 displayed a median increase in ET of 10% compared to C0T0 and falls between a reduction of 5% by elevated CO_2 and an increase of 19% by warming (**Figure 2c**). The effect of drought on annual ET was more extreme, with a 20-45% reduction in ET compared to C0T0. The effects of all climate manipulation treatments on seepage appear analogous (e.g., ET increase results in reduced seepage) and roughly proportional to the effects on ET. Altogether, we provide a detailed and consistent account of how individual and interactive global change factors can alter the water budget of an energy-limited grassland. This globally unique dataset provides critical experimental evidence of direct hydrological implications of climate change—information that will serve invaluable as many terrestrial ecosystems transition from energy-limited (access to solar radiation) to water-limited (hydrologically stressed) systems.[16] Further details can be found in Forstner, et al. [25]

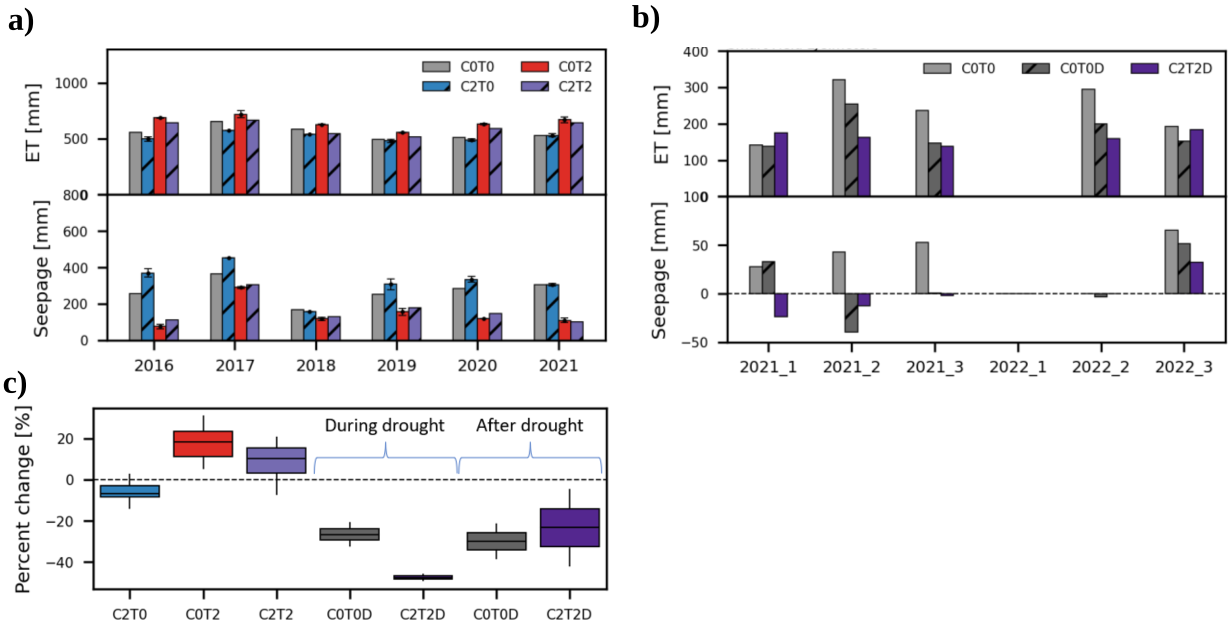

Figure 2. Major components of the water budget from lysimeters from the six core climate manipulation treatments spanning the 2016-2022 growing seasons. Large weighable lysimeter (C0T0: *n* = 1; C2T0: *n* = 2; C0T2: *n* = 2; and C2T2: *n* = 1) information is displayed in **a)**, SmartField Lysimeter (SFL) information (C0T0: *n* = 1; C2T0: *n* = 2; C0T2: *n* = 2; and C2T2: *n* = 1) on a per-cut basis in **b)**, and **c)** shows percent deviation from C0T0 evapotranspiration (ET) for the years 2016-2022 via combining records from large lysimeter and SFL's. See **Figure 1** for treatment code description.

*Elevated CO_2 increased **<u>water use efficiency</u>** during dry periods and alleviated drought-stress on biomass production [amplified by warming and reduced with simulated drought]*

In ClimGrassHydro, WUE was studied both as instantaneous flux-based (using canopy chambers) and seasonal biomass yield parameters. Contrary to the water budget results, plant responses to hydrological effects of our climate manipulation treatments are complex, time variable, and appear to be heavily driven by prevailing local meteorological conditions. Chamber-derived WUE was often more influenced by seasonal cuts (**Figure 3a**) and their associated seasonal ranges of VPD (**Figure 3b**) than climate manipulation treatments (**Figure 4**). Despite the overall sporadic and variable effects of climate manipulation on WUE, key periods of water stress appear to highlight differences in plant response between treatments. For example, peak drought periods in 2020 (**Figure 4a**) and 2021 (**Figure 4b**) consistently produced higher WUE values for C2T2 relative to C2T2D.

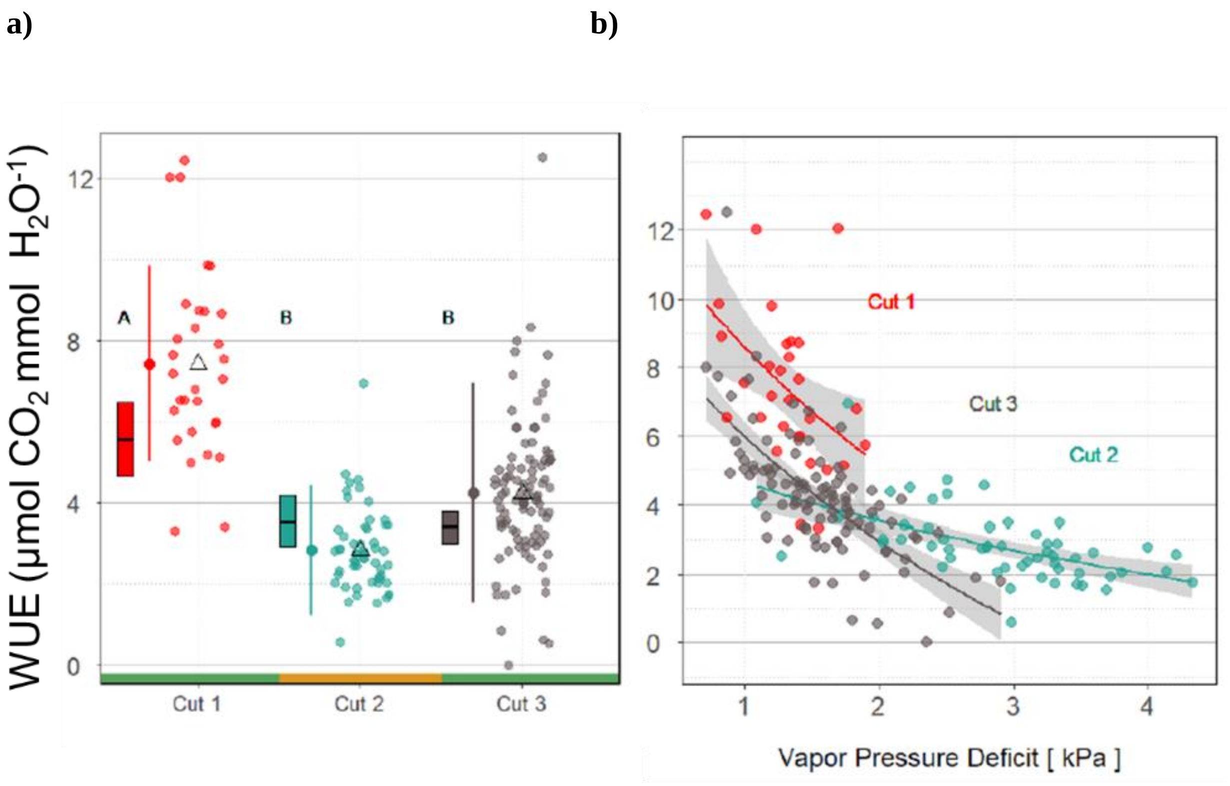

Figure 3. Canopy chamber-based water use efficiency (WUE) from the 2021 growing season as a function of **a)** grass cut cycle and **b)** vapor pressure deficit (VPD). In **a)** lines and points represent raw data whereas boxplots depict statistical model predictions where VPD and photon flux density are covariates. Overall, seasonal cuts and prevailing meteorological conditions often had stronger effects than climate manipulation treatments. *Different letters* denote statically significant differences ($p < 0.05$).

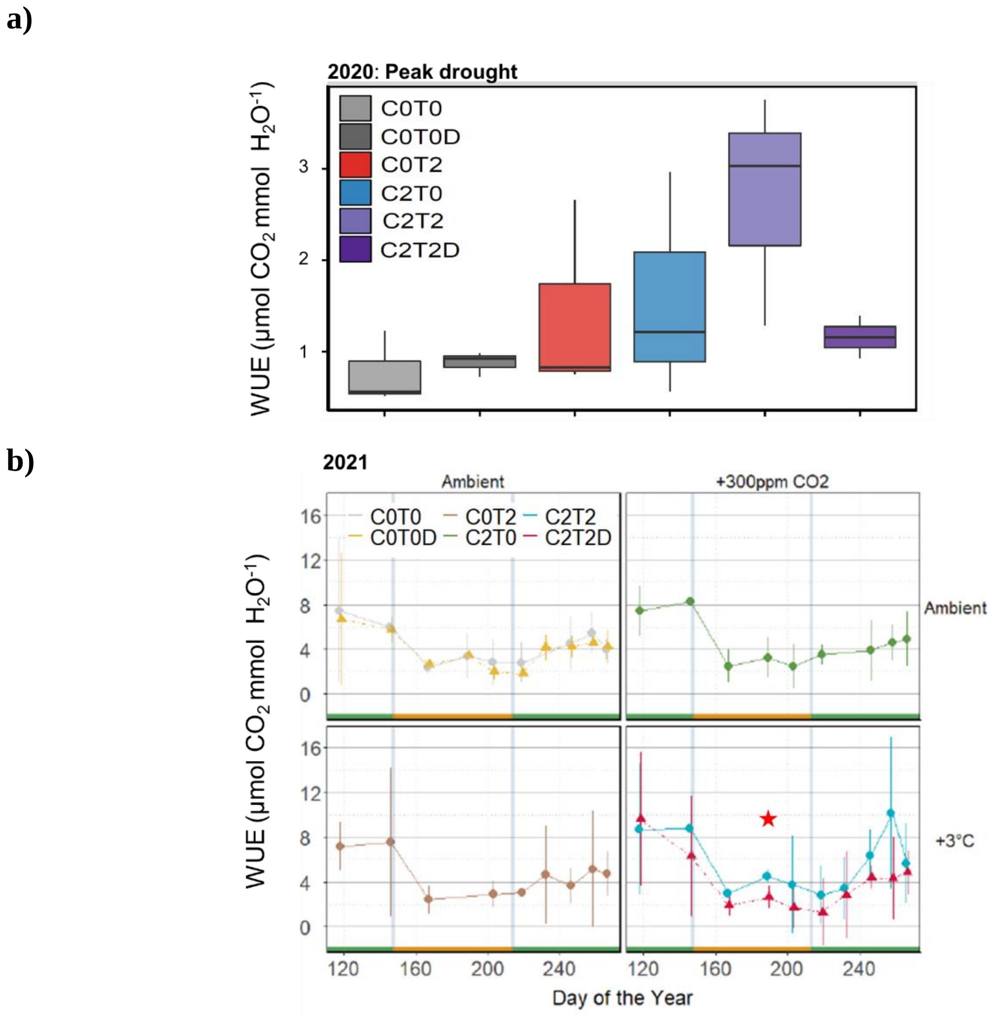

Figure 4. WUE derived from periodic canopy chamber measurements for 6 core climate manipulation treatments (C0T0: *n* = 4-6; C2T0: *n* = 3; C0T2: *n* = 3; C2T2: *n* = 3-4; C0T0D: *n* = 3-4, and C2T2D: *n* = 3-4). We show **a)** peak drought WUE in the 2020 growing season and **b)** the full 2021 growing season. The red star in **b**) isolates sections of the 2021 drought where C2T2 and C2T2D differ most.

We further analyzed grassland yield in relation to seasonal ET obtained by lysimeters to understand plant growth responses to a changing climate and water stress.[25] Forstner, et al. [25] found lower yield anomalies for plots exposed to elevated CO_2 relative to ambient conditions under the most extreme natural dry spell found at the site between 2018-2020 (**Figure 5**). More directly, reduced losses of plant biomass for C2T0 and C2T2 in 2019 suggest that elevated CO_2 has the potential to buffer drought-induced water stress on plant growth. In contrast, some time periods without water stress showed positive effects of warming on yield (**Figures 5** and **A1**). Overall—in our energy-limited grassland—we periodically see growth benefits of warming to plants (at little expense to water loss) early in the growing season when the system is cool and wet, but only observe growth benefits from elevated CO_2 under exceptional water stress.

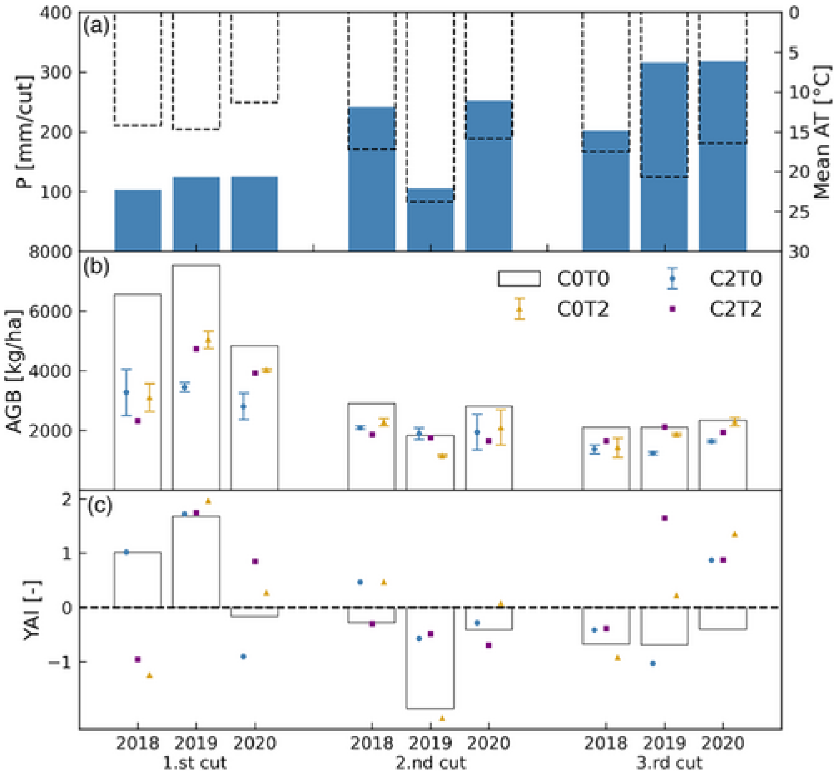

Figure 5. **a)** Precipitation (P) and average air temperatures (T_{avg}) at the experimental site, Irdning-Gumpenstein (ZAMG), **b)** aboveground biomass on a dry matter basis(AGB) and **c)** Yield Anomaly Index (YAI) derived from large weighable lysimeters (C0T0: *n* = 1; C2T0: *n* = 3; C0T2: *n* = 2; and C2T2: *n* = 1) for each cutting event from 2018 to 2020 (from Forstner, et al. [25]). See **Figure 1** for treatment code description.

Climate change can alter the distribution of ***root water uptake (RWU)****: recurring drought forced consistent shift of RWU to deeper soil water [deeper shifts when combined with warming and elevated* CO_2*]*

Unlike the very time-constrained effects of climate manipulation on WUE, climate manipulation has a clear and persistent effect on root water uptake distribution (**Figure 6**). We used a soil moisture-derived technique[26] to estimate root water uptake for 2017, 2019, and 2020 for the six core treatments. We show that the distribution of RWU is significantly deeper in recurring drought plots, with the strongest (and deepest) effect observed in the C2T2D treatment. Further details can be found in Tissink et al. (*in prep*).

The ***fraction of transpiration to ET (T/ET)*** *is reduced during (ambient) and even following drought when +T, +*CO_2 *and drought are combined*

To further explore the hydrological stresses of drought on plant water use, we partitioned transpiration from the bulk evapotranspiration flux using stable isotope signatures from periodic chamber measurements and high resolution records of soil water signature. We show that the ratio of transpiration to ET (T/ET) dropped dramatically from the beginning to the peak of our 2021 simulated drought—with the lowest T/ET observed in C2T2D plots (**Figure A2; Figure 7**).

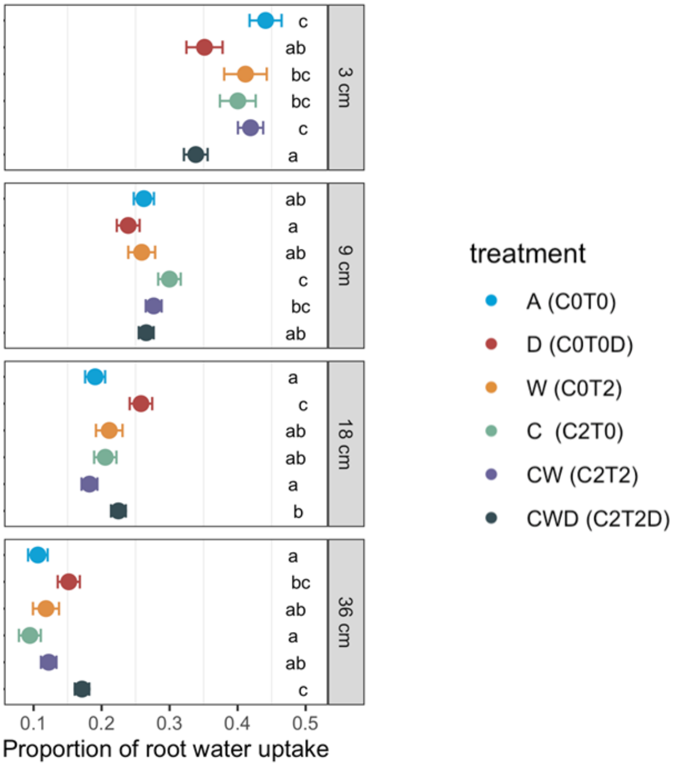

Figure 6. Proportional root water uptake (RWU) across the soil profile from 2017, 2019, and 2020 (from Tissink et al., in prep). Different letters denote statically significant differences between treatments ($p < 0.05$). See **Figure 1** for treatment code description.

Following the 2021 drought simulation, we applied a deuterium labeled (3000 ‰ δ^2H) 40 mm precipitation event across all treatments to closely trace the movement of water through soil, plant, and atmospheric fluxes of water. We consistently detected lower T/ET values for C2T2D relative to other treatments, suggesting that plants had reduced RWU and thus a lower proportional contribution of T to ET. This altogether showed that extreme drought conditions can alter plant water use responses during and following the water stress period. Further, this reduction in T/ET may have both changed the quantity and source of transpiration—the largest terrestrial flux of water.[27] Further details can be found in Radolinski et al. (in prep-a).

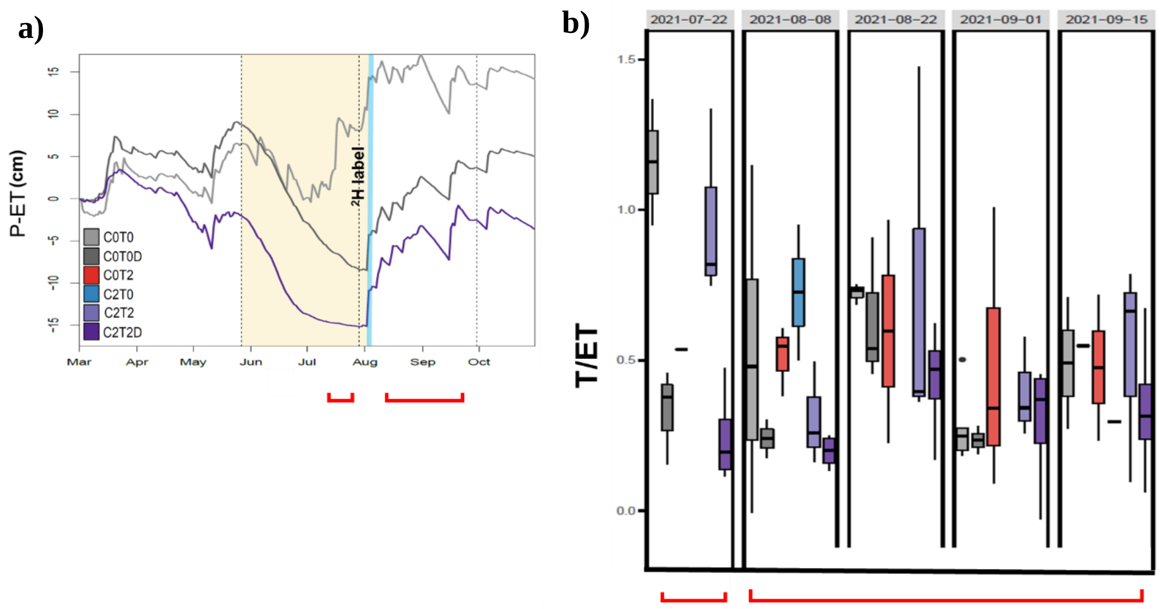

Figure 7. a) Cumulative precipitation minus evapotranspiration as an indicator of the treatment-specific climatic water balance from SmartField Lysimeters (SFLs) in the 2021 growing season. **b)** ratio of transpiration to evapotranspiration fluxes using ^{18}O signatures from transpiration and evapotranspiration chambers (C0T0: *n* = 4-6; C2T0: *n* = 3; C0T2: *n* = 3; C2T2: *n* = 3-4; C0T0D: *n* = 3-4, and C2T2D: *n* = 3-4) and an evaporation source obtained from high resolution monitoring from soil membrane tubes at 3 cm below-ground. See **Figure 1** for treatment code description.

*Climate change altered the **source, age, and transit** of water through (“older”) ET flux and drainage [enhanced by warming with elevated CO_2 and with drought]*

We observed a distinct pattern of water transport through systems exposed to a combination of elevated CO_2, warming, and recurring drought (**Figures A3** and **8**). Namely, the C2T2D treatment showed an exceptionally high retention of the post-drought labeled water relative to other treatments (**Figures A3**), even with numerous rainfall events in the late growing season. For example, the time lapsed from our rewetting event to peak isotope label signatures at 36 cm was greater by a factor of 25 in C2T2D compared to C0T0D (**Figure 8b**). This translated to higher label signature strength for C2T2D in transpiration, bulk ET water (**Figure A4**), and throughout the soil profile—resulting in high retention of “older” water in the system for longer durations (**Figure A5**). Interestingly, this pattern of transport persisted despite C0T0D having a larger overall drawdown of moisture during the 2021 drought (**Figures A3** and **7a**) and both drought treatments producing significant seepage at 60 cm (**Figure 8**). The overall C2T2D water deficit, however, was more extreme by the end of the rainfall suppression period (P-ET in C0T0 = 8 cm, C0T0D = -8 cm, and C2T2D = -15 cm; **Figure 8a**) which may have stressed the system far more than other treatments.

The total water deficit during drought simulation had a strong influence—not only on soil water movement—but also on plant water use following the rewetting (**Figures 7** and **8**). Though the tracer strength subsided towards pre-label values after ~30 days in transpiration and ET (**Figures A4** and **8c**), older rewetting water appears to have redistributed within the soil profile (**Figure A5**) and re-supplied transpiration during a natural dry period 45 days after rewetting. This effect was apparent for the six main treatments; however, the soil water redistribution and shifting of water use was most extreme for the C2T2D treatment (**Figure 8c**). High residual tracer mass in deep root zone drainage (**Figure 9a**) suggests that plants in the C2T2D treatment had altered water use strategy and lowered tracer outflow through transpiration (**Figure 7**). This resulted in a loss of 85% of the applied tracer mass through the lower C2T2D rootzone after 200 days of monitoring compared to just 38% in the C2T2 and 30% in C0T0D (**Figure 9a**).

Further, the transport mechanics of this future drought treatment differed from that of other climate manipulation scenarios. We fit a process-based soil hydrological model (Hydrus 1D or H1D) to high resolution, soil moisture and soil tracer records to better quantify the mass of drainage fluxes within the soil profile. The best-fit H1D results clearly indicate that the proportion of this older tracer water leaving the lower rootzone was far greater (and for far longer) in the C2T2D treatment relative to other climate change scenarios (**Figure 9a**). The median transit time of C2T2D in the deep root zone was nearly 3 times that of its non-drought counterpart, C2T2 (**Figure 9a**). It should be noted; however, that both drought treatments were predicted to have required far less new precipitation water to remove or displace similar quantities of tracer mass (**Figure 9b**). Though, the greater difference between tracer breakthrough curves relating pore water ^{2}H signatures to saturated versus mean moisture pore volumes transited, suggest that the bulk of transport through the future drought soil may have been restricted to a smaller range of pore space (**Figure 9b**). This hinted that the extreme climate change scenario, C2T2D, may have altered the partitioning of water below-ground. Further details can be found in Radolinski et al. (in prep-a).

Mixing *of newly infiltrating precipitation with pre-event soil water storage was severely restricted in "future" drought soil—a* ***hydrological disconnection*** *in pore space*

To further explore possible mixing anomalies with subsurface storage, we used all available 2021 precipitation input and soil water tracer signatures and amounts to project a rolling, per-

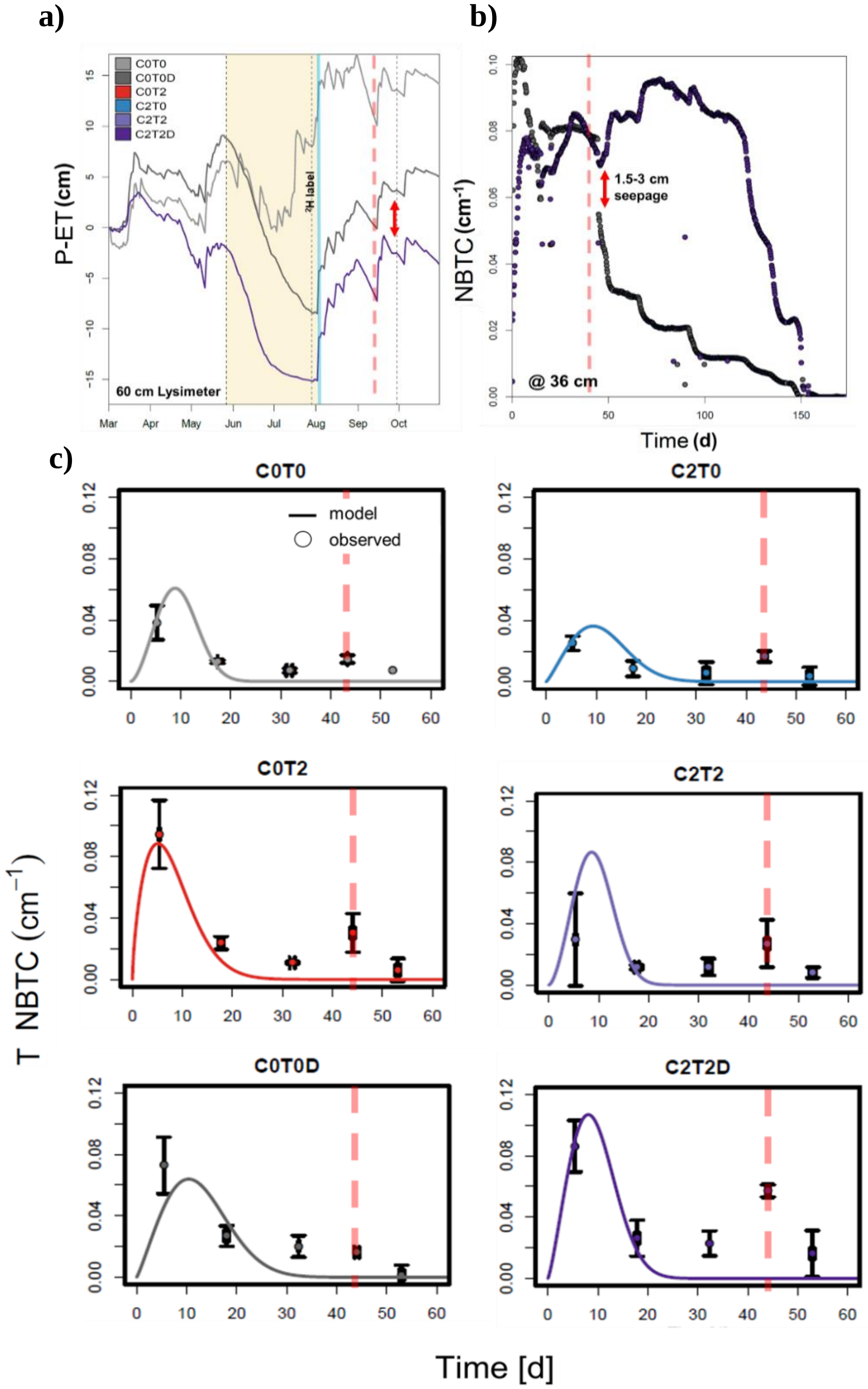

Figure 8. **a)** Growing season climatic water balance expressed as cumulative precipitation minus (P-ET) from SmartField Lysimeters (SFL's) in the 2021 growing season and **b)** the post-label stable isotope signature of 36 cm soil water (n = 1 per treatment) normalized to the pre-label and label signature and volume or normalized breakthrough concentration (NBTC) in dimensions of L^{-1}. **c)** Normalized post-label breakthrough curve using isotope records from leaf transpiration chambers (C0T0: *n* = 4-6; C2T0: *n* = 3; C0T2: *n* = 3; C2T2: n = 3-4; C0T0D: *n* = 3-4, and C2T2D: *n* = 3-4). Lines in **c)** represent a steady state dispersion modeled (Weibull distribution) of water transit. Red arrows depict a significant rainfall period where 10-30 mm of seepage was collected from drought treatments. Red dashed lines represent a natural drawdown period following the label. See **Figure 1** for treatment code description.

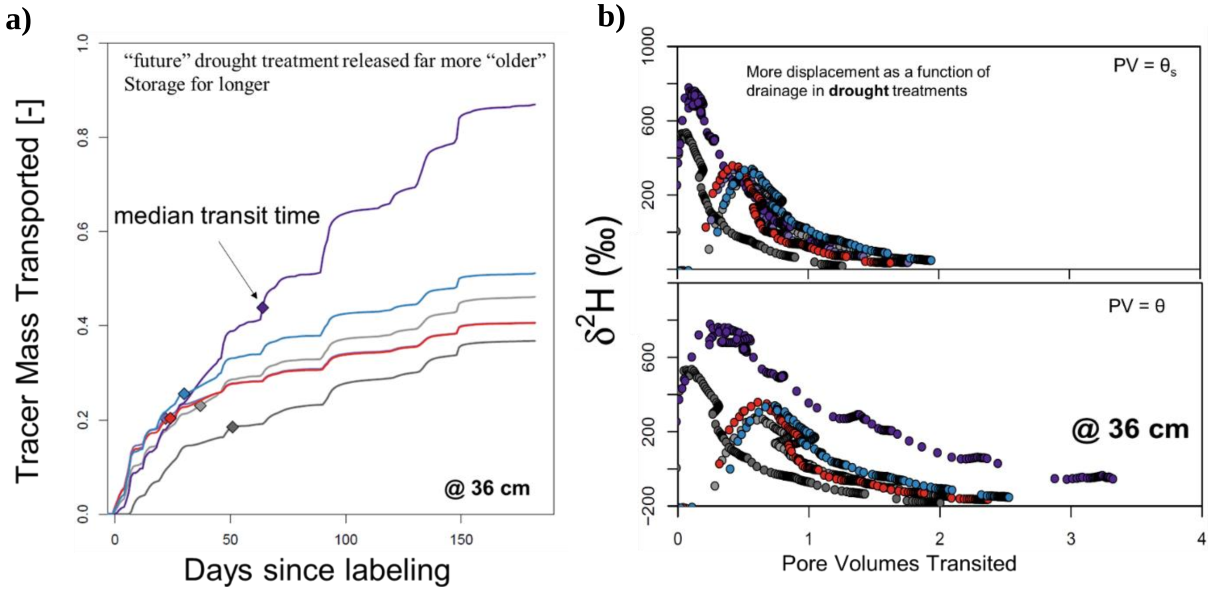

Figure 9. a) H1D modeled cumulative transit time distribution of lower root zone drainage (36 cm) for the 6 core treatments, with median transit times displayed as diamonds. **b)** Breakthrough curves relative soil pore water tracer signatures versus saturated (**top**) and mean soil moisture (**bottom**) pore volumes. See **Figure 1** for treatment code description.

treatment, 100% mixing projection across the measurement period. For the non-drought climate manipulation treatments, the weighted soil water isotope signatures nearly match mixing projections following the application of the 2021 label (**Figure 10**). Alternatively, the measured ambient recurring drought treatment values appears to deviate notably from the mixing projection during the natural post-drought drawdown period, but exhibits strong mixing dynamics in the later growing season. The C2T2D treatment, however, showed extreme mixing anomalies for the entirety of the post-label period. These unprecedented results suggest that 1) recurring drought can significantly alter the partitioning of water through the rootzone and 2) this effect is drastically amplified by elevated CO_2 and warming. We provide a globally unique window into potential future mechanisms of soil water movement and give detailed insight into realistic mixing anomalies in the vadose zone—a topic that is intensely debated in current water research.[28-32] Further details can be found in Radolinski et al. (in prep-a).

<u>Hydrological disconnections</u> *across the soil profile were strongest with the combination of elevated* CO_2 *and warming*

In an additional analysis, we used 4-7 years of high frequency soil moisture records from 74 sensors and 4-6 soil depths spanning all 7 climate manipulation levels to precisely quantify changes to the cycling of soil root zone water. We used spectral techniques[33] to transform soil moisture time series into the frequency domain and analyze their deviations from surface boundary drivers of ET (VPD) and inputs (precipitation) across the soil profile. We find that cycling of the shallow-most root zone soil water (3-10 cm) is well connected to that of deeper root zone water (36-50 cm) for ambient and isolated CO_2

enrichment (+150–300 ppm) conditions (**Figure 11**). Alternatively, warming (+1.5-3°C) appears to provide a detectable separation across the soil profile.

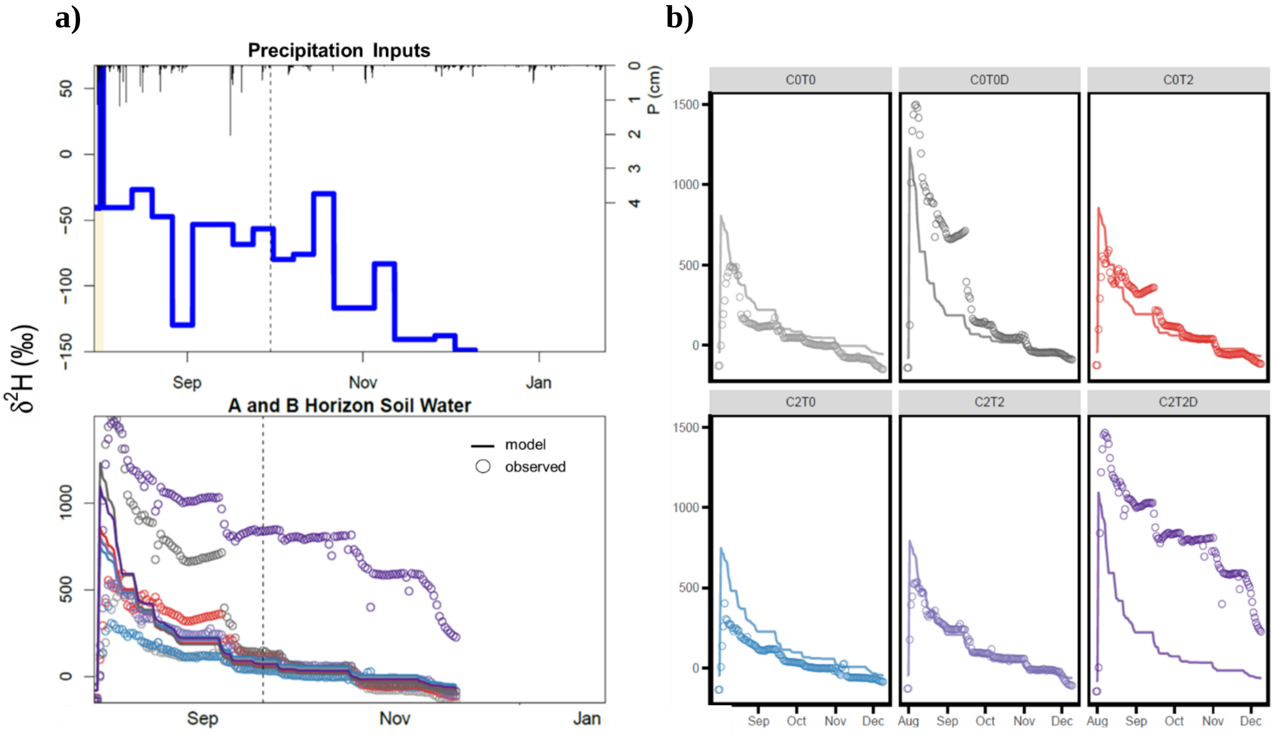

Figure 10. In **a)** we show 2021 post-label daily accumulation and weekly ^{2}H signatures of precipitation and volume-weighted pore water deuterium signatures with 100% rolling mixing projection lines. Mixing lines assume that, from the beginning of the monitoring period onwards, each precipitation event mixed completely with pre-event storage. We additionally break-down these comparisons per treatment in **b)**. See **Figure 1** for treatment code description.

The combination of warming and CO$_2$ enrichment amplifies this effect and provides a clear separation from shallow versus deep root zone water. The combination of warming and elevated atmospheric CO$_2$, has likely increased the occurrence of a near-surface moisture buffer layer as plants close their stomata in response to periodic water stress and CO$_2$ enrichment. We believe that this could have forced a hydrological disconnection across the soil profile. Further details can be found in Radolinski et al. (in prep-b).

*Elevated CO$_2$ or air temperature alone may increase **NO$_3^-$ transport** to groundwater and alter travel time, whereas the combination of the two factors can reduce losses.*

Following the 2021 deuterium label, nitrate transport from our montane grassland root system was highly dependent on prevailing climate manipulation treatments. Climate alterations without recurring drought appear to increase overall NO$_3^-$ transport relative to ambient conditions (**Figure 12**), despite similar water transport patterns (**Figures 9**)—likely reflecting varying biogeochemical responses. Warming increases NO_3- transport with time, whereas elevated CO_2 combined with warming may partially reduce these losses. The combination of elevated CO_2, warming, and drought resulted in larger periodic “pulses” of NO_3^- combined with rapid water transport. Further details can be found in Radolinski et al. (in prep-c).

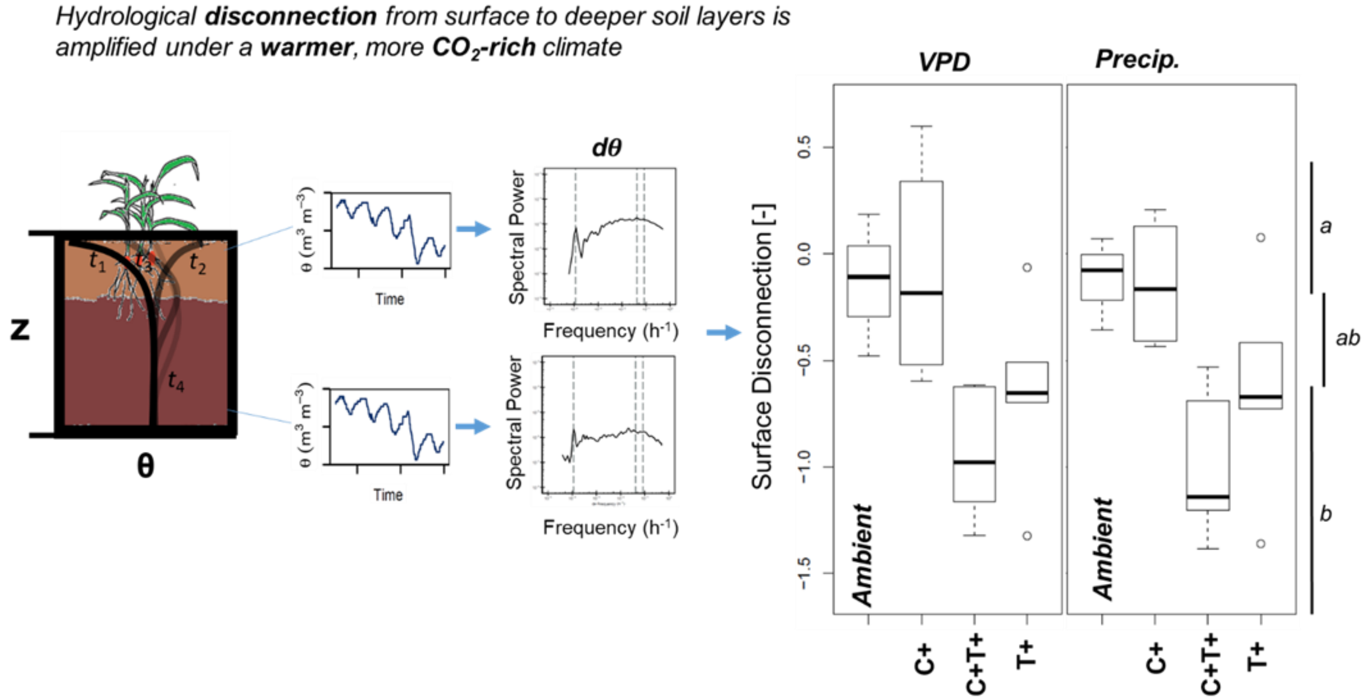

Figure 11. Depiction of spectral analyses of long-term soil moisture records. Here we used 4-7 years of high frequency (15 min aggregated to 1h) soil moisture records from 74 sensors and 4-6 soil depths spanning all 9 climate manipulation levels to detect climate-change driven alterations to soil moisture cycling. The “surface disconnection” metric is the difference between average rolling Pearson correlation coefficient relating entire soil moisture derivative (*dϑ*) to surface forcing conditions (VPD and precipitation) power spectra between upper-most (3-10 cm) versus lower-most (36-50 cm) root zone. “C+” denotes +150–300 ppm CO_2 enrichment and “T+” indicates +1.5-3°C warming. *Different letters* denote statically significant differences ($p < 0.05$). See **Figure 1** for treatment code description.

Altogether, we show that 1) various global change factors can produce distinct patterns in nitrate transport and 2) these patterns are likely driven more by prevailing biogeochemical differences rather than variations in soil hydrological characteristics.

*Climate change altered the **physical and hydraulic properties** of soil especially during dry periods [enhanced by warming with elevated CO_2 and with drought]*

We explored potential climate change-derived changes to soil physical and hydraulic properties through (a) a series of destructive sampling events in 2019 and 2021 (**Figure 13a**).; and (b) inverse modeling using HYDRUS-1D (**Figure 13b**). Differences between the ambient and drought treatments were observed mainly in the lower B soil horizon. The effects of drought on soil porosity appear to be mixed and may ultimately resemble that of controls. Alternatively, field capacity and bulk density was also found to be lower in systems exposed to drought. A more static total porosity and a reduced field capacity with lower bulk density in drought plots may indicate an increased occurrence of larger, more conductive soil pores (e.g., macropores, persistent soil cracks, etc.).

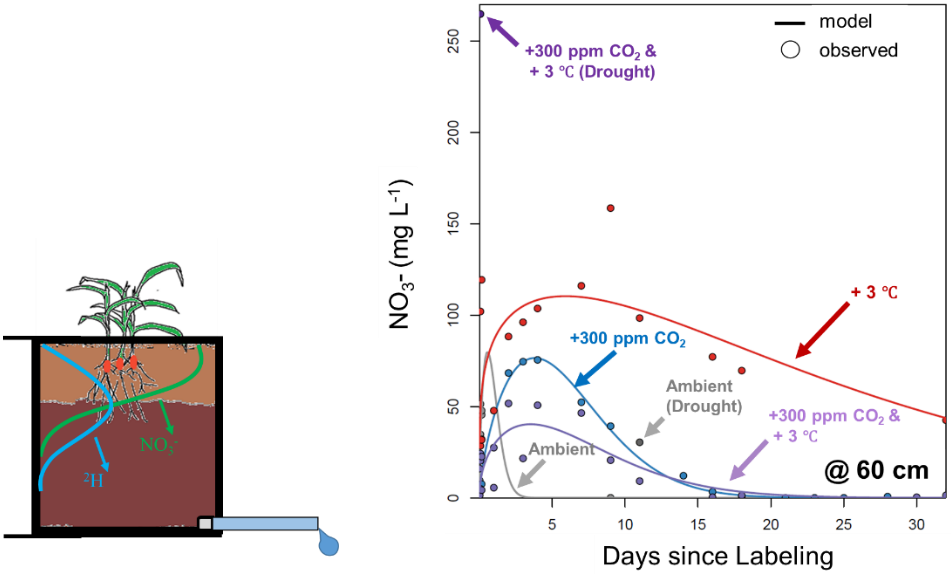

Figure 12. Nitrate breakthrough patterns in B horizon soil water via suction cup samples (points) and modeled dispersive transport using a Weibull distribution (lines). Data follow an intense (75 mm h -1) 4 cm labeled precipitation even in August of 2021.

This finding is in line with soil water mixing and retention anomalies in drought treatments following the 2021 labeling. However, there seemed to be no effect on the wilting point, indicating that the driest range of soil moisture retention (and smallest pores) may have not been altered by our drought simulations. Saturated hydraulic conductivity, a soil-specific constant and measure of saturated water movement, was higher in the A horizon for drought plots and in the B horizon in 2019 for all treatments. However, these effects were not observed in 2021 and further research is needed to fully understand the dynamics at play.

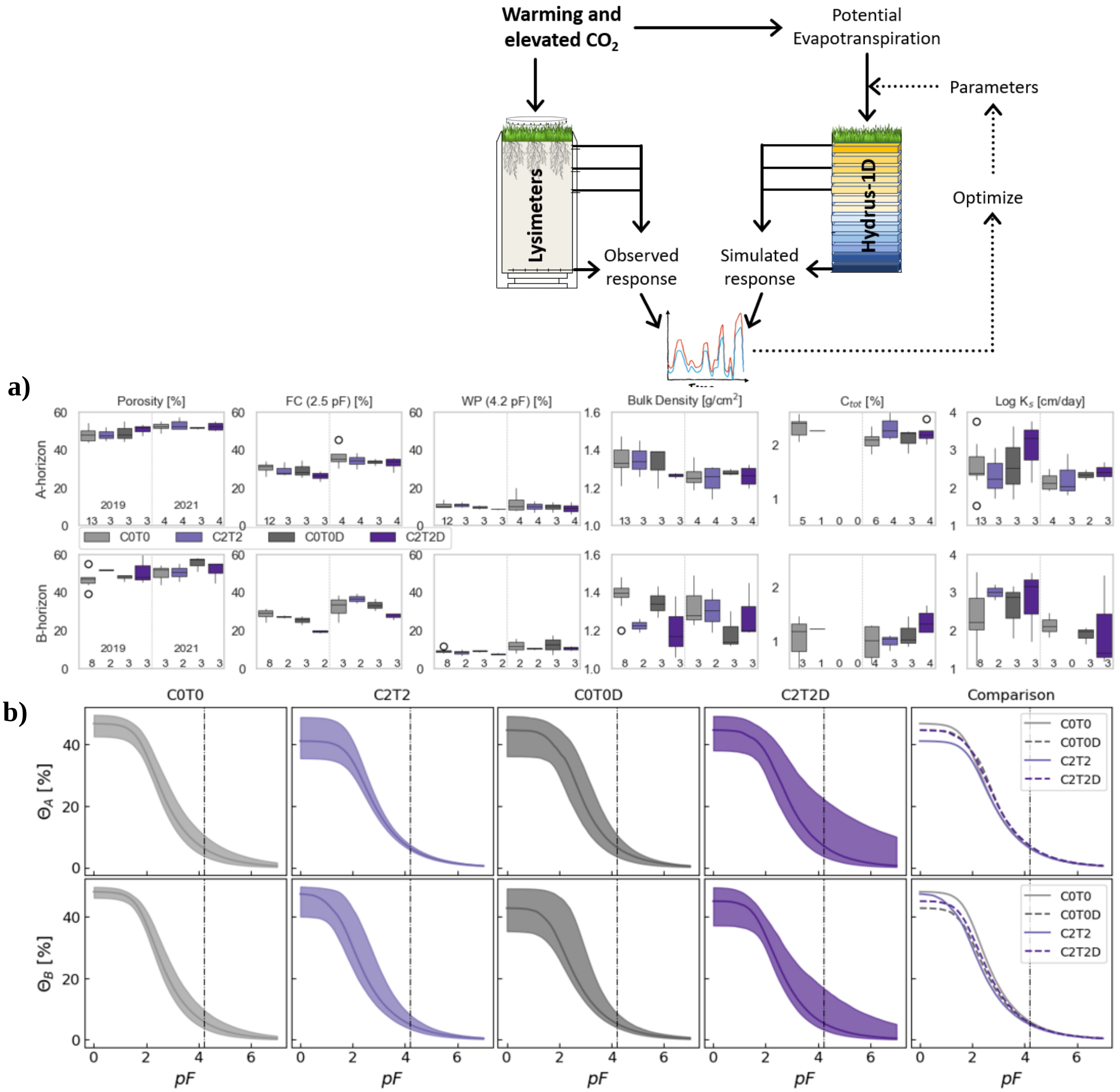

Figure 13. Top) Simple graphical depiction of inverse modeling exercise. **a)** Soil hydraulic properties for each treatment obtained from laboratory measurements of undisturbed soil cores taken in autumn 2019/2021. We display soil porosity, field capacity (FC), permanent wilting point (WP), bulk density, total carbon content, and saturated hydraulic conductivity K_s for the two key soil horizons (A is derived from 5-10 cm and B is from 35-30 cm soil cores). Sample size, *n*, is given at the bottom of each panel. Soil water retention curves obtained from inverse modeling using HYDRUS-1D, with soil water content, isotope concentration and WP4C measurements used in the objective function. Lines represent the median prediction, while the uncertainty bands show the 95% confidence interval (**b**). See **Figure 1** for treatment code description.

Altogether, recurring drought treatments seemed to have shifted these agricultural soils to a state in which they hold soil water less effectively in a normal moisture range and potentially transmit water more rapidly through an increased macroporosity. We detail consistent changes to soil hydraulic properties induced by climate manipulation, however, more long term monitoring may be necessary to distinguish transient features driven by hysteresis from persistent and plastic changes (see **Figures A6**, **A7**, and **A8**).

Work package 2 (model-based analyses and upscaling)

In this work package, we aimed to quantify the effects of ecohydrological responses on water yield at different spatial scales. To achieve this, we employed three different modeling approaches. At the plot level, we first used a Penman-Monteith model adjusted for elevated CO_2 concentrations. This allowed us to quantify the individual ecohydrological responses to warming and elevated CO_2 concentration by inverse modeling, based on actual evapotranspiration and leaf area index measurements taken at the lysimeters **(1)**. Using HYDRUS-1D, we estimated the effective soil hydraulic parameters and quantified soil water budget components such as seepage, evaporation, and transpiration at the plot scale **(2)**. To transfer our findings from the plot level to the catchment scale, we used a process-oriented Community Water Model (CWatM) (Burek et al.[36]) and three simple rainfall-runoff models **(3)**. Overall, our goal was to gain a deeper understanding of the implications of ecohydrological responses on water yield at different spatial scales.

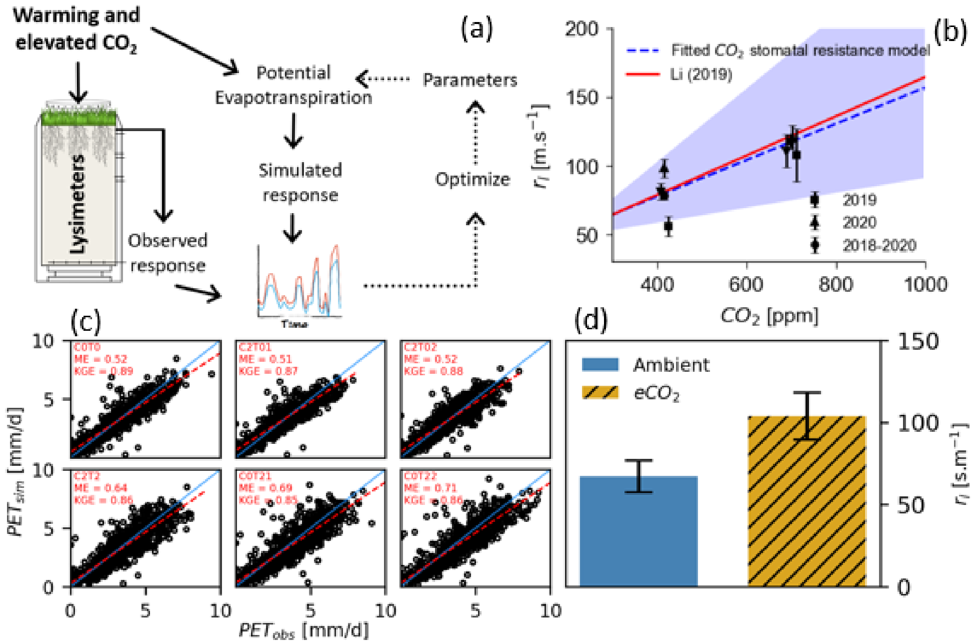

Figure 14. a) Schematic representation of the workflow to estimate the sensitivity of stomatal resistance to elevated CO_2 concentration. **b)** Fitted relationship between stomatal resistance (rl) and CO_2. **c)** Comparison between simulated PET and observed PET at the lysimeters. **d)** Estimated stomatal resistance for ambient conditions and elevated CO_2 conditions (+300 ppm CO_2) (Adapted after Vremec et al.[38]).

Climate change altered transpiration through stomatal closure [+CO_2 increased stomatal resistance and decreased transpiration; no observed +CO_2 fertilization effect]

Previous FACE experiments (Leakey et al.[37]) reported that elevated atmospheric CO_2 concentration leads to stomatal closure (reduced transpiration) and may lead to increased plant growth (CO_2 fertilization). To understand the ecohydrological reponse of managed montane grasslands to elevated atmospheric CO_2, we quantified the effect of CO_2 on plant cover using leaf area index measurements from the plots, while the effect of CO_2 on stomatal resistance was quantified using the approach presented in Vremec et al.[38] (**Figure 14a,b,c**). Leaf area index data showed no general effect of elevated CO_2 concentration, while a decrease in transpiration due to stomatal closure was observed in all CO_2 treated treatments. Stomatal resistance increased by 40-50% between ambient and CO_2 -treated plots (**Figure 14d**). The effect of CO_2 was similar for both ambient and heated conditions. The results of our study suggest that while elevated CO_2 concentration may not have a significant effect on leaf area index at our study site, it does lead to an increase in stomatal resistance.

Transferring generalized plot findings to the catchment scale

To understand the effects of ecohydrological responses on runoff generation at the catchment scale, we used the Community Water Model (CwatM) developed by Burek et al.[36] and three simple lumped parameter models (GR4J, HYMOD, HBV) to transfer findings from the plot scale. The nearby Gulling catchment (**Figure 15**), which is located close to the experimental facility and is almost 50% of various types of grassland, was an ideal location for the study. The modeling scenarios differ from each other in terms of input potential evapotranspiration, which was designed to mimic the C0T0, C2T0, C0T2, and C2T2 treatments from the plot scale. We compared the catchment-level models to HYDRUS-1D simulations at the plot level, using meteorological data for the period 1990-2016 to account for local climate variability.

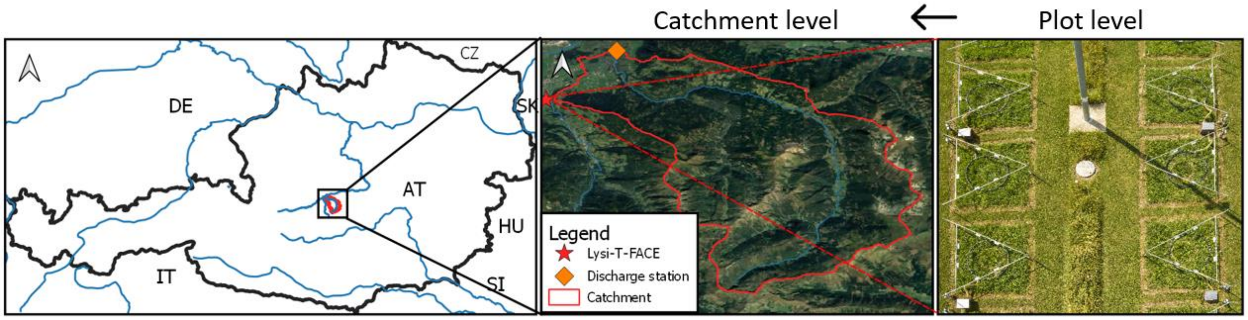

Figure 15. The figure illustrates the location of the Gulling catchment in relation to the experimental site. The catchment, shown in the middle figure, is geographically situated in close proximity to the experimental site. The Gulling catchment is highlighted in red, and the location of the experimental site is indicated with a red marker.

Climate change effect on potential evapotranspiration were enhanced at the catchment [enhanced +T effect; dampened + CO_2 effects, enhanced effects of +T in higher elevations]

Based on the estimates of potential evapotranspiration at the catchment level, the following conclusions can be drawn: (1) Dampened effects of elevated atmospheric CO_2 concentration at the catchment scale, as only 50% of the catchment is made up of grassland, and the potential evapotranspiration for the other 50% was not considered to be sensitive to elevated CO_2 concentrations (**Figure 16a,c**); (2) Increased effects of warming at the catchment scale due to the system's greater sensitivity to warming (such as higher wind speeds and lower vapor pressure deficits) (**Figure 16a,b**); (3) Increased effects of temperature on evapotranspiration in higher elevation zones, where evapotranspiration tends to be more sensitive to warming (**Figure 16b**).

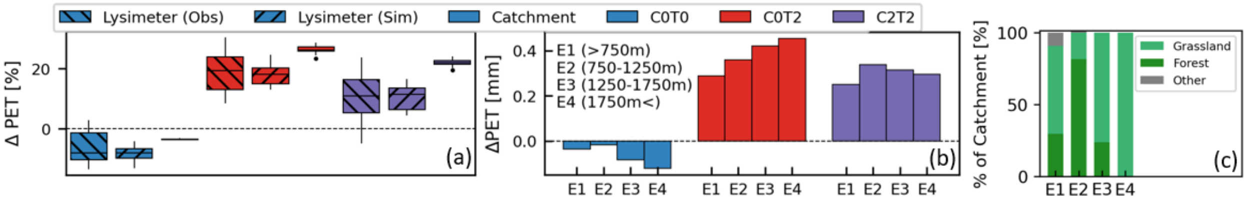

Figure 16. a) Response of potential evapotranspiration (PET) to elevated CO_2 concentration (C2T0), warming (C0T2), and a combination of both (C2T2) at plot level (observed and simulated) and for the catchment (simulated) . **b)** The elevation dependent sensitivity of PET to elevated CO_2 concentration and warming. **c)** Percentage of land cover per elevation band.

Climate change effects enhanced for green (ET) but buffered for blue (runoff) water fluxes at the catchment level [buffered due to higher precipitation; enhanced +T effects on actual ET at the catchment; hydrological response enhanced under drier conditions at plot level]

The effect of warming on green (ET) water fluxes are enhanced at the catchment scale, particularly in higher elevation zones, due to the increased sensitivity of evapotranspiration to warming (**Figure 16b**). However, the effects on blue water fluxes (runoff and percolation) are dampened as the catchment receives more precipitation (approximately + 500mm/year) than at the plot level. This means that while evapotranspiration may change significantly, the relative change in percolation or runoff is not as significant (**Figure 17a**). The highest deviations in annual percolation can be observed at the plot level (using HYDRUS-1D-HD), where dry periods have a greater impact on percolation (**Figure 17b**).

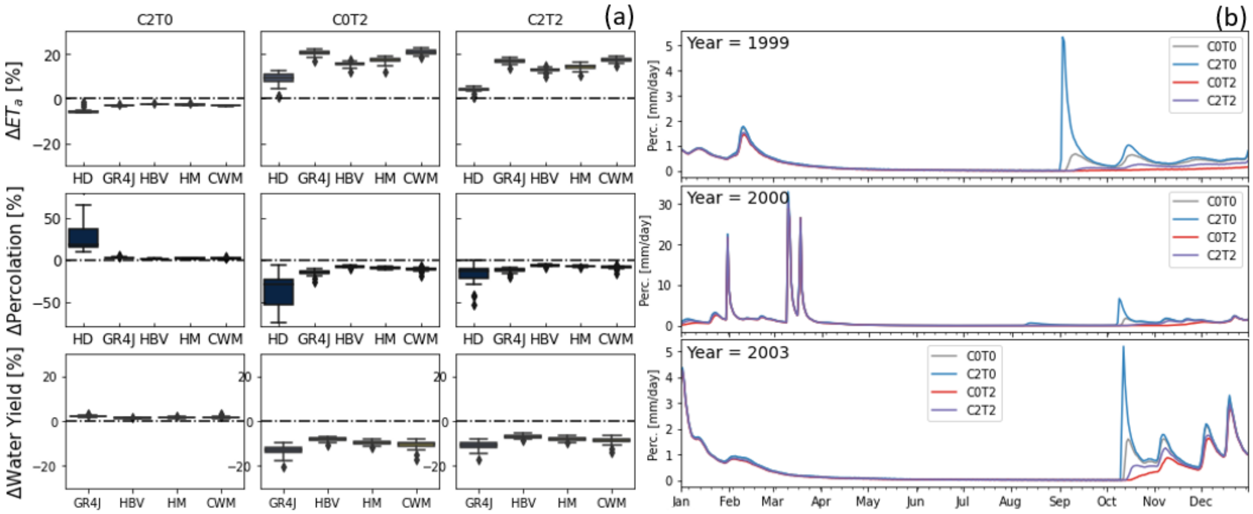

Figure 17: a) Modeled actual evapotranspiration (ETa), percolation, and water yield responses to elevated CO_2, warming, and their combination compared to ambient conditions for HYDRUS-1D (HD), GR4J, HBV, HYMOD (HM), and CWatM (CWM). **b)** The hydrological response to different climate treatments is enhanced after dry summer periods at the plot level (HYDRUS-1D). See **Figure 2** for treatment code description.

Open-Source Products

During thethe project, various software packages were developed to address gaps in existing solutions. **PyEt** and **Phydrus** are notable examples, as they are both open-source and freely available. PyEt is a Python package that considers the effects of climate change and model uncertainty when estimating potential evapotranspiration. Phydrus, on the other hand, was developed to integrate the Fortran-based HYDRUS-1D into the Python environment, allowing for coupling between HYDRUS-1D and other Python packages that simplify the use of sensitivity and uncertainty analyses. Both of these Python packages are available under the MIT license on the Python Package Index and are developed as community projects on Github (https://github.com/pyet-org/PyEt, https://github.com/phydrus/phydrus).

A multi-model comparison of ecosystem processes and water use under global change

Ecosystem manipulative experiments such as ClimGrassHydro are a highly valuable resource for evaluating and improving land surface models, our main tools for predicting the future of ecosystems under future conditions. We performed a multi-model data synthesis, using a set of the most widely used land surface models (CABLE, CLM5, DALECGRASS, ED2, ELM, GDAY, JULES, LDNDC, LPJGUESS, QUINCY, ORCHIDEE, SDGVM). All models were run using standardized protocols and site-level meteorological forcing for all experimental treatments of ClimGrassHydro. We show that all models overestimate the biomass growth response to elevated CO_2 and further do not predict any interactive responses between increased temperature and CO_2. Due to the overestimate in CO_2 response, the models can also not represent drought response under future climate. These results are extremely valuable as they identify modeling gaps and outline a path for future model improvement. This study highlights the importance of manipulative experiments in the context of ecosystem modeling as such insights into model performance are difficult if not impossible to obtain from simple observational studies.

Further relevant work related to ClimGrassHydro

ClimGrassHydro supported the publication of two broader papers focussing on the effects of drought in a future world, where drought events are suggested to increase in frequency and severity and are also expected to increasingly affect non-dryland regions (IPCC 2021). In the review paper by Müller and Bahn (2022) we synthesize the current understanding of drought legacies at the scale of species, communities and ecosystems and develop hypotheses on how an increasing frequency and severity of drought can lead to cascading responses involving mechanisms of adaptation and degradation. In the perspective paper by Grünzweig et al. (2022) we highlight a broad range of mechanisms typical of dryland ecosystems, which under future climate conditions may play an increasing role in currently non water-limited ecosystems.

ClimGrassHydro also supported a multiyear synthesis study on the single factor- *versus* interactive effects of warming, elevated CO_2 and drought on grassland productivity, which is currently in preparation for publication. Furthermore, a study using two key species from the ClimGrass experiment tested for the effects of drought intensity on the relationship between resistance and recovery across a range of productivity parameters (Ingrisch et al. 2023). Considering the importance of nitrogen cycling for productivity and drought recovery as well as nitrate leaching (see below), Maxwell et al. (2022) analyzed the drivers of N cycling in response to elevated CO_2, warming, and drought. We observed a shift in the control of soil protein depolymerization, from plant substrate controls under elevated CO_2 and warming to controls via microbial turnover and soil organic N availability under drought. Finally, we participated in a European cross-site study exploring the potential of mulitspecies phytometers for disentangling climate from soil nutrient effects on plant biomass production (Wilfahrt et al. 2021).

At the first ClimGrassHydro stakeholder workshop (see WP3) a consistent interest was expressed in how various climate change factors would affect the movement of nitrate through soils. To address this topic in more detail, a grant proposal was then submitted (by ClimGrassHydro members: Jesse Radolinski, Markus Herndl, and Michael Bahn) and funded through the Tiroler Wissenschaftsförderung (TWF), to the study the effects of global change on nitrate transport. The core analysis for this grant follows the 2021 deuterium label and nitrate transport through soil pore water (**Figure 12**).

Summary of key scientific findings and broader implications

In summary, ClimGrassHydro obtained the following key findings:

1) *Warming (+T) and elevated CO_2 altered the* ***water budget****: elevated CO_2 alone increased seepage and decreased evapotranspiration (ET), while warming alone, and warming with elevated CO_2 did the opposite*
2) *Elevated CO_2 increased* ***water use efficiency (WUE)*** *during dry periods and alleviated drought-stress on biomass production [amplified by warming and reduced with simulated drought]*
3) *Climate change altered the distribution of plant* ***root water uptake (RWU)****: recurring drought forces consistent shift of RWU to deeper soil water [deeper shifts when combined with warming and elevated CO_2]*
4) *The* ***fraction of transpiration to ET (T/ET)*** *was reduced during (ambient) and even following drought when warming, elevated CO_2 and drought were combined*
5) *The* ***source and age*** *of summer ET and soil drainage water were dramatically altered when warming and elevated CO_2 were combined with recurrent drought*
6) *The* ***mixing and cycling*** *of soil water were significantly altered when warming and elevated CO_2 were combined with water stress—driving hydrological disconnections in space and time*
7) *Soils exposed to warming, elevated CO_2, and water stress displayed altered* ***physical and hydraulic properties***
8) *Elevated CO_2 or air temperature alone increased* ***NO_3- transport*** *to groundwater and altered travel time, whereas the combination of the two factors can reduce losses.*
9) *The effect of warming on ET was greater at the* ***catchment-scale****, yet* ***water yield*** *was less affected due to additional precipitation.*

As Earth's hydrological cycle increasingly intensifies,[34,35] the need to understand the ecohydrological implications of a changing climate grows. We provide—for the first time—novel and direct insight into potential scenarios of Earth's near-surface hydrology under global change. We find not only consistent effects of a changing climate on the annual water budget, but we also detect changes that extend from plant production and water use to physical properties of flow belowground. More directly, we find that systems exposed to frequent water stress, warming, and elevated CO_2 appear to host vegetation that conserve water use and soils that transmit water more rapidly through macropores and resist mixing with a soil matrix that holds soil moisture. These globally unique datasets were further used to numerically model and project various permutations of climate into the future and across scales. ClimGrassHydro, altogether, represents a critical step in understanding the full impact of Earth's rapidly changing climate on water resources.

Work package 3 (transdisciplinary integration and dissemination)

The aim of WP 3 was to develop a platform for transdisciplinary exchange and integration of knowledge with climate economics and stakeholders from the agricultural and energy sectors. This was addressed by two major cross-sectors stakeholder workshops scheduled at the beginning and towards the end of the project's running time, which involved also the other three projects from the 'groundwater cluster' of the ÖAW-ESS program. In addition, a dedicated stakeholder workshop and an expert conference were organized, involving stakeholders from the agricultural sector. Furthermore, results of ClimGrassHydro were presented at multiple interdisciplinary conferences and conference sessions and within the frame of the multidisciplinary Doctoral Colleges 'Alpine Biology and Global Change' (University of Innsbruck) and 'Climate Change – Uncertainty, Thresholds, Coping Strategies' (University of Graz). Finally, several targeted publications were prepared addressing stakeholders at the national and international scale.

The first stakeholder workshop was held at the University of Graz in February 2020. It was attended by 33 participants, including the project representatives from the four 4 ÖAW groundwater cluster projects and the stakeholders from the agriculture, water and energy sectors. After the presentations of the four projects two plenary discussions and a group discussion were held with the goal to make the project dissemination as targeted as possible, to include available stakeholder knowledge into the projects, to identify relevant topics not yet sufficiently addressed by the projects and to identify possible fields of conflict concerning water resources. The following topics were identified as most interesting to the stakeholders: 1) availability of water in the future, 2) groundwater quality (nitrate levels in seepage water) and recharge rates, 2) nitrate balance, soil fertility and agricultural yield, 3) combined approaches that take other land use changes under consideration, 4) recommendations for land use and grassland irrigation. All participants indicated that they wanted to be informed further on ClimGrassHydro and the other projects of the ÖAW groundwater cluster. As the second point was not immediately addressed by the groundwater cluster in an agricultural context, a complementary project was applied for, focusing on nitrate transport and leaching from managed grassland during drought and subsequent rewetting (Radolinski et al., funded by the Tiroler Wissenschaftsfonds). For some first results see the WP1 report.

Based on the feedback and interest expressed in the stakeholder workshop, we developed the conceptual outline for possible fact sheets, which we based on a questionnaire, prioritizing the topics we wanted to address and identifying possible inputs from the ClimGrassHydro project in relation to the relevant literature. We decided to have two fact sheets, the first one focusing more strongly on an agricultural perspective (and most closely associated with ClimGrassHydro), and the second on addressing water management with a more strongly hydrological perspective. The first draft of the fact sheet emerging from ClimGrassHydro was presented and discussed at a dedicated stakeholder workshop, which was part of the '8. Umweltökologisches Symposium', held in Raumberg-Gumpenstein in March 2022. This workshop was held online for covid-related reasons and to involve as many participants as possible, covering the range from ministry experts to practitioners. The feedback from the workshop was used for improving and aligning the fact sheet, which was again opened for broader discussion at the ÖAW groundwater cluster workshop / closing event in October 2022, held at Universität für Bodenkultur in Vienna. At this third stakeholder workshop, the fact sheet, next to other key findings of ClimGrassHydro and of the other three ÖAW groundwater cluster projects, were presented to and discussed with 29 experts and stakeholders from the agricultural and water sectors.

While the water management-related fact sheet is still in preparation, the fact sheet targeting the agricultural sector has meanwhile been reviewed by external experts and is being revised and finalized for publications as part of the fact sheet series of the Climate Change Centre Austria. The fact sheet (Bahn et al., in press) provides a broadly accessible synthesis of the context and the latest scientific state of the art (including key findings from ClimGrassHydro) on the effects of climate extremes on managed grassland, with particular focus on the situation in Austria. It furthermore includes an overview of major management and adaptation options.

In addition, the ÖAW groundwater cluster jointly published an article presenting the four projects and their perspectives in the applied journal Wasserland Steiermark, addressing primarily stakeholder and practitioners (Birk et al. 2020).

Key results of ClimGrassHydro were presented and discussed, next to the mentioned three stakeholder workshops, also at two national and international expert- and stakeholder conferences on 'Wetterextreme: Perspektiven in Monitoring und Vorhersage' (Leipzig, June 2022) and '22. Alpenländisches Expertenforum' (Raumberg-Gumpenstein, November 2022). Furthermore, next to a larger number of disciplinary presentations at international conferences, ClimGrassHydro was presented at a widely attended interdisciplinary conference session (solicited talk at the EGU2020-session 'Climate Extremes, Tipping Dynamics, and Earth Resilience in the Anthropocene') and at the largest multidisciplinary global mountain conference (Innsbruck Mountain Conference 2022), which hosted more than 800 participants.

Finally, ClimGrassHydro supported a major international publication advancing the conceptualization of social-ecological resilience and outlining major challenges for operationalizing the resilience concept with particular focus on climate extremes (Thonicke et al. 2020). This publication, emerging from a Future Earth cross community workshop on "Extreme Events and Environments from Climate to Society", identifies multiple pathways within adaptation and mitigation strategies, which could enhance the adaptive capacity of social-ecological systems to absorb climate extremes.

Dissemination and follow-up activities

1) Publications

Publications in peer-reviewed international journals:

Thonicke, K., Bahn M., Lavorel, S., Bardgett R.D., Erb K., Giamberini, M., Reichstein M., Vollan B., Rammig A. (2020) Advancing the understanding of adaptive capacity of social-ecological systems to absorb climate extremes. *Earth's Future* 8 (2) e2019EF001221, doi.org/10.1029/2019EF001221

Forstner, V., Groh J., Vremec, M., Herndl M., Vereecken, H., Gerke, H. H., Birk S., Pütz T. (2021) Response of water fluxes and biomass production to climate change in permanent grassland soil ecosystems. *Hydrology and Earth System Science* 25: 6087–6106, doi.org/10.5194/hess-25-6087-2021

Ogle, K., Liu Y., Vicca, S., Bahn M. (2021) A hierarchical, multivariate meta-analysis approach to synthesising global change experiments. *New Phytologist* 231: 2382-2394. doi.org/10.1111/nph.17562

Wilfahrt, P.A., Schweiger, A. H. Abrantes, N., Arfin-Khan, M. A. S., Bahn, M., Berauer, B. J., Bierbaumer, M., Djukic, I., van Dusseldorp, M., Eibes, P., Estiarte, M., von Hessberg, A., Holub, P., Ingrisch, J., Schmidt, I. k., Kesic, L., Klem, K., Kröel-Dulay, G., Larsen, K. S., Lõhmus, K., Mänd, P., Orbán, I., Orlovic, S., Peñuelas, J., Reinthaler, D., Radujković, D., Schuchardt, M., Schweiger, J. M. I., Stojnic, S., Tietema, A., Urban, O., Vicca, S., Jentsch., A. (2021) Disentangling climate from soil nutrient effects on plant biomass production using a multispecies phytometer. *Ecosphere* 12 (8). doi.org/10.1002/ecs2.3719.

Grünzweig, J.M., De Boeck, H.J., Rey A., Santos M.J., Adam O., Bahn M. et al. (2022) Dryland mechanisms could widely control ecosystem functioning in a drier and warmer world. *Nature Ecology & Evolution* 6: 1064 – 1076.

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Bahn, M., Reinthaler, D., Piepho, H.P., Pötsch E., Schaumberger A., Herndl M. and the ClimGrass team. Single versus interactive effects of warming, elevated CO_2 and drought on productivity and stoichiometry in montane grassland. (*in prep*)

Caldararu, S., Zaehle., and the ClimGrass team. A multi-model comparison of ecosystem processes and water use under global change (*in prep*)

Radolinski, J., Vremec, M., Wachter, H., Birk, S., Brüggemann N., Herndl, M., Kahmen, A., Kübert, A., Schaumberger, A., Stumpp, C., Werner, C., Bahn, M. Drought in a warmer, more CO_2-rich climate restricts plant water use and soil water mixing. (*in prep*)

Radolinski, J., Kirchner, J., Herndl, M., Bahn, M. Hydrological disconnection from surface to deeper soil layers is amplified under a warmer, more CO_2-rich climate. (*in prep*)

Radolinski, J., Vremec, M., Herndl, M., Brunetti, G., Stumpp, C., Harris, E., Schaumberger, A., Kahmen, A., Birk, S., Bahn, M. Soil nitrogen nitrogen transport under a warmer, more CO_2 rich, and drought prone climate. (*in prep*)

Tissink, M., Radolinski, J., Reinthaler, D., Pötsch, E., Bahn, M. Individual vs. interactive global change effects on root traits and water uptake in a mountain grassland. (*in prep*)

Vremec, M., Radolinski, J., Brunetti, G., Forstner, V., Herndl, M., Stumpp, Bahn, M., Birk, S. Drought Resilience in a Montane Grassland: Impacts of Intense Drought on Water Resources/Intense Drought Impairs water retention and plant water availability in a montane grassland (*in prep*)

Vremec, M., Burek, P., Guillaumot, L., Radolinski, J., Forstner, V., Herndl, M., Stumpp, Bahn, M., Birk, S. (In preparation) Modeling montane grassland hydrology under a changing climate: from plot to catchment level (*in prep*)

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2) Presentations at international and national conferences

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Vremec, M., Radolinski, J., Forstner, V., Herndl, M., Stumpp, C., Birk, S., Bahn, M.: Climgrasshydro: Ecohydrology of mountain grassland under multiple global change. 48th IAH Congress, Brussels, 06.09.2021.

Bahn, M., Sommerdürre und die Resilienz von Grasland im globalen Wandel. Tagung Wetterextreme: Perspektiven in Monitoring und Vorhersage, Leipzig, 01.06.2022.

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Bahn, M. (2023) Drought legacies and ecosystem responses to subsequent drought. 2023 Ecological Society of America Annual Meeting, Portland (USA) (invited talk, *upcoming*)

3) Organization of international and national scientific meetings and stakeholder workshops

Birk, S. (2020) Convener Session HS8.2.1 How to assess climate change impacts on groundwater and what are the tipping points in hydrogeology? European Geosciences Union (EGU) General Assembly, Vienna (online), 07.05.2020

Bahn, M., Zaehle S. (2021) Co-convener Session: BG3.25 Terrestrial ecosystem responses to global change: integrating experiments and models to understand carbon, nutrient, and water cycling.
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Radolinski J. (2022) Co-convener Session: HS10.5 Stable isotopes to study water and nutrient dynamics in the soil-plant-atmosphere continuum. European Geosciences Union (EGU) General Assembly 2022, Vienna, 30.04.2021.

Bahn, M. (2022) Convener Session: Mountain grasslands under global change. International Mountain Conference (IMC2022), Innsbruck, 12.09.2022

Bahn M. (2022) Co-convener / Chair Synthesis Session: Mountain Ecosystems under Global Change. International Mountain Conference (IMC2022), Innsbruck, 15.09.2022.

Birk, S. (2022) Co-convener Session: HS8.1.7 Climate change and groundwater: impacts, adaptation and opportunities. European Geosciences Union (EGU) General Assembly, Vienna, 23.05.2022

Caldararu, S., Bahn M. (2023) Co-conveners Session: Vegetation functional responses to global change across multiple methods and scales. European Geosciences Union (EGU) General Assembly 2023, Vienna (*upcoming*).

Radolinski J. (2023) Co-convener Session: HS10.5 Stable isotopes to study water and nutrient dynamics in the soil-plant-atmosphere continuum. European Geosciences Union (EGU) General Assembly 2022, Vienna, (*upcoming*).

Expert conference

Schaumberger A, Herndl M (2022) 22. Alpenländisches Expertenforum, Raumberg-Gumpenstein, 8.11.2022

Stakeholder workshops

Stakeholderworkshop Wasserressourcen im Klimawandel: Konsequenzen für Wasser-, Energie- und Landwirtschaft, Graz, 7.02.2020.

Stakeholderworkshop im Rahmen der Tagung 8. Umweltökologisches Symposium 2022 (online), 22.03.2022.

Stakeholderworkshop Wasserressourcen im Klimawandel: Konsequenzen für Wasser-, Energie- und Landwirtschaft, Vienna, 27.09.2022.

4) Dissemination in media and podcasts

Podcastserie :/> Klimawandel - Anpassungsstrategien (raumberg-gumpenstein.at)

Effekt von Dürre auf Ökosysteme viel stärker als bisher gedacht. In: science.apa vom 30.03.2022

Dürre: Realität übertrumpft Experiment. In: orf.at vom 30.03.2022

Dürre stresst Pflanzen stärker als gedacht. In: Der Standard vom 04.05.2022.

Studies showcase long-term effects of drought. APA (Austrian Press Agency) Interview featured in the Newsroom of the University of Innsbruck (https://www.uibk.ac.at/de/newsroom/2022/studien-zeigen-die-langzeiteffekte-von-durre) 26.09.2022.

Greenhorn-Science Podcast “Lebensraum Boden” (2022)
https://open.spotify.com/episode/4GgYthRA2f63asbz7VmeLR

5) University theses and student reports

Guyard, S., (2020) Effects of warming, elevated CO_2, and drought on root water uptake and its relation to root traits. University of Innsbruck and ENGEES École Nationale du Génie et de l'Eau et de l'Environnement de Strasbourg (French National School for Water and Environmental Engineering) (Engineering internship report).

Tissink, M., (2020) The effects of climate change on grassland ecohydrology. University of Innsbruck (MSc thesis).

Mempiot, J., (2021) Ecohydrological processes in mountain grasslands under global change. University of Innsbruck and ENGEES École Nationale du Génie et de l'Eau et de l'Environnement de Strasbourg (French National School for Water and Environmental Engineering) (Engineering internship report).

Halais, C., (2021) Effects of warming, elevated CO_2, and drought on root water uptake and its relation to root traits. University of Innsbruck and ENGEES École Nationale du Génie et de l'Eau et de l'Environnement de Strasbourg (French National School for Water and Environmental Engineering) (Engineering internship report).

Putz, G., (2021) The effects of a future climate and drought on a managed mountain meadow. University of Innsbruck (BSc thesis).

Geiger, A. (2022) Impact of manipulated drought under future climate conditions on gas exchange of *Dactylis glomerata* and *Plantago lanceolata* in an Austrian alpine grassland ecosystem. University Freiburg (MSc thesis).

Cunow, J. (2022) Individual and combined effects of elevated CO_2, warming, and drought on water-use-efficiency and productivity in a montane grassland. University of Innsbruck (MSc thesis).

Vremec, M. (2023) Impacts of warming and elevated CO_2 on the hydrology of montane grassland. University of Graz (upcoming PhD thesis).

6) University-based teaching

involved a.o. the Doctoral Colleges “Alpine Biology and Global Change” (University of Innsbruck) and “Climate Change – Uncertainty, Thresholds, Coping Strategies” (University of Graz)

Master student classes “Ecological project study” (2021) and “Selected topics in Ecology and Environmental Management” (2020-2023) at the University of Innsbruck

Student 4 Student Summer School - S4SSS, Obergurgl (2022) organized by the University of Innsbruck

7) Projects and other activities related to / emerging from ClimGrassHydro

“Characterizing different trajectories of nitrate transport in a changing climate” funded by the Tiroler Wissenschaftsförderung (TWF) with PI Jesse Radolinski (PI), Markus Herndl (Co-PI), and Michael Bahn (Co-PI). The study the effects of global change on nitrate transport. Core analysis for this grant follows the 2021 deuterium label and nitrate transport through soil pore water.

ClimGrassThermo (2021-2022; PI: Michael Bahn), which was funded by the Ministery for Agriculture, Regions and Tourism jointly with several Provincial Governments, equipped the ClimGrass sites with thermal infrared cameras to test for the canopy temperature dynamics as indicators for productivity, phenology, water use and stress in grassland and was highly complementary and therefor coupled to the ongoing experimental work of ClimGrassHydro.

The project “IrriGrass”, intended to elaborate in more detail on the irrigation demands in relation to grassland productivity and therefore emerging and connecting directly from the work pursued in ClimGrassHydro, was unsuccessfully applied for within of the ACRP (Austrian Climate Research Program) call of the Austrian Climate and Energy funds.

COST Action: WATSON (WATer isotopeS in the critical zONe) is an EU funded network of researchers and stakeholders which centers its interest on the Critical Zone, the dynamic skin of the Earth that extends from vegetation canopy to groundwater. WATSON collects, integrates, and synthesizes current interdisciplinary scientific knowledge on the partitioning and mixing of water in the critical zone taking advantage of the unique tracing capability of stable water isotope. Several ClimGrassHydro members are heavily active in WATSON activities. Christine Stumpp is a working group coordinator, Jesse Radolinski presented at a WATSON plenary meeting in 2021 in Ljubljana, Slovenia, and Angelika Kuebert will give an invited talk in April. The three of them are also involved in multiple review papers being prepared as deliverables to the COST action.

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Appendix

2021 drought effects on SFL plant yield and ET.

Both the C0T0D and C2T2D treatments showed a decrease in AGB during the second cut (simulated drought period) in 2021 (**Figure A1**), with the decrease being more severe in the C2T2D treatment. In contrast, C2T2D showed the highest AGB in the early season.

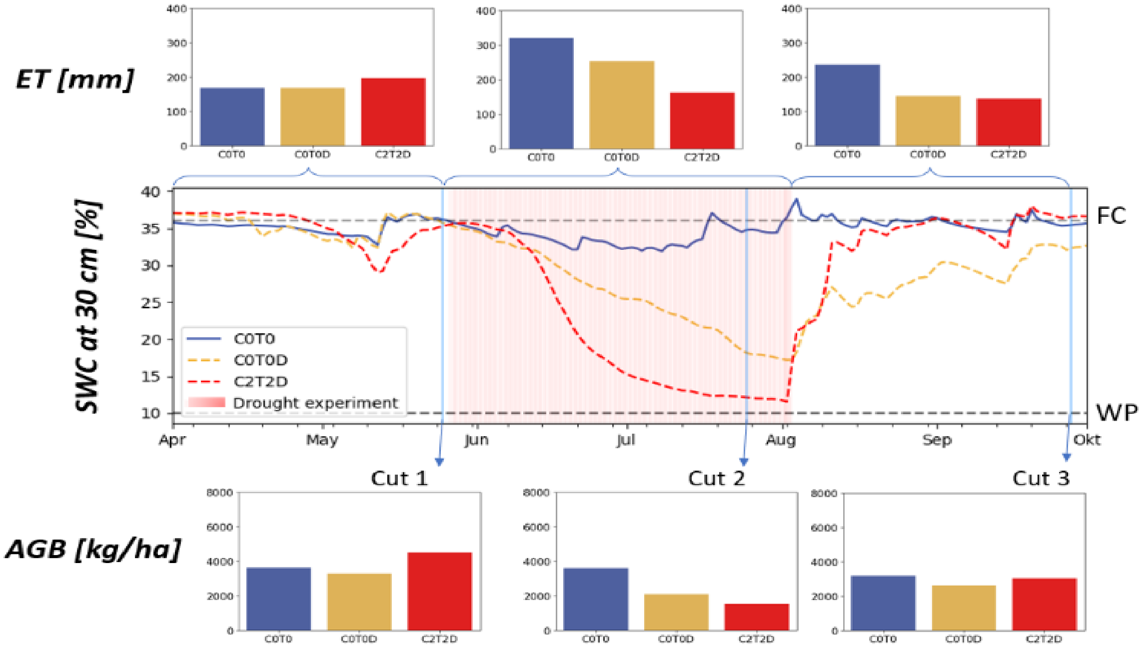

Figure A1. Per-cut aggregations of SmarField Lysimeter (SFL) evapotranspiration (ET), soil moisture at 30 cm, and above-ground biomass for the 2021 growing season). See **Figure 2** for treatment code description.

2021 pre-label T/ET

Here we show the T/Et ratios before the rewetting label in 2021 (**Figure A2**).

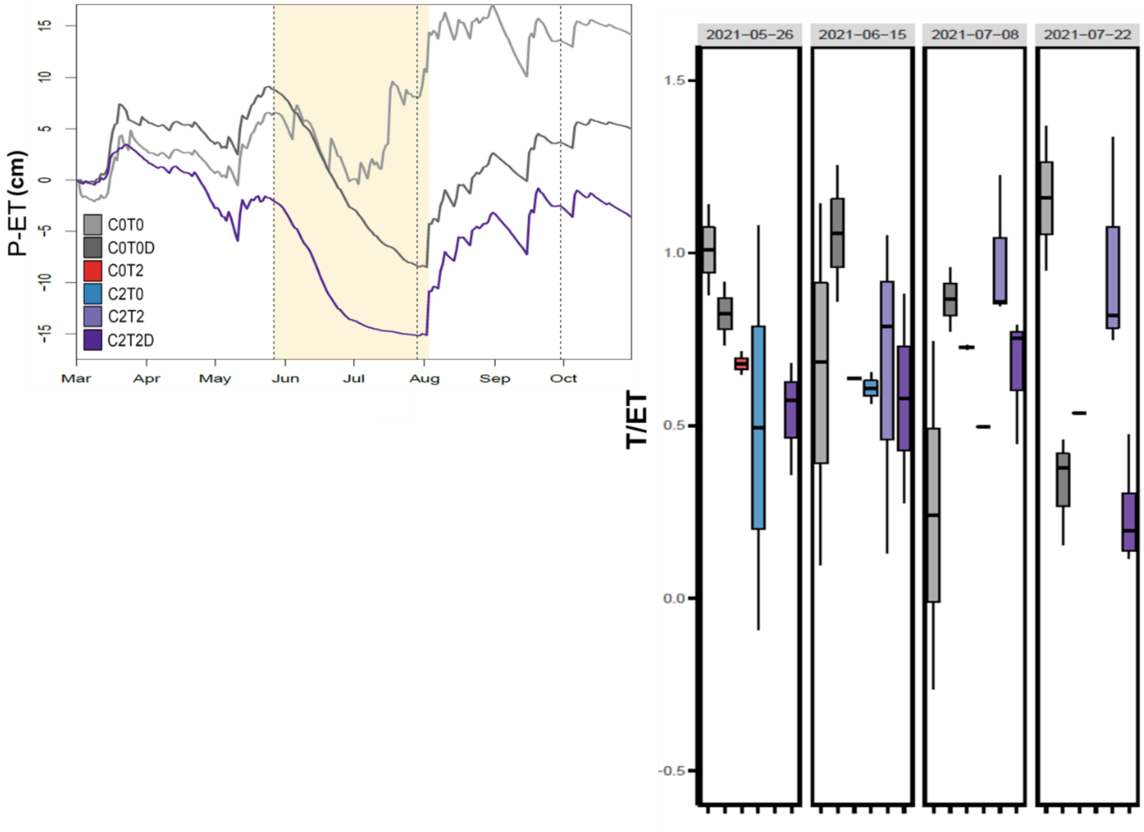

Figure A2. left) Cumulative precipitation minus evapotranspiration from SFLs in the 2021 growing season. **Right)** ratio of transpiration to evapotranspiration fluxes using ^{18}O signatures from transpiration and evapotranspiration chambers and an evaporation source from high resolution monitoring below-ground (at 3 cm).

2021 lower rootzone tracer signature post-label

Here we show the 36 cm soil moisture and NBTC values following the rewetting label in 2021 (**Figure A3**).

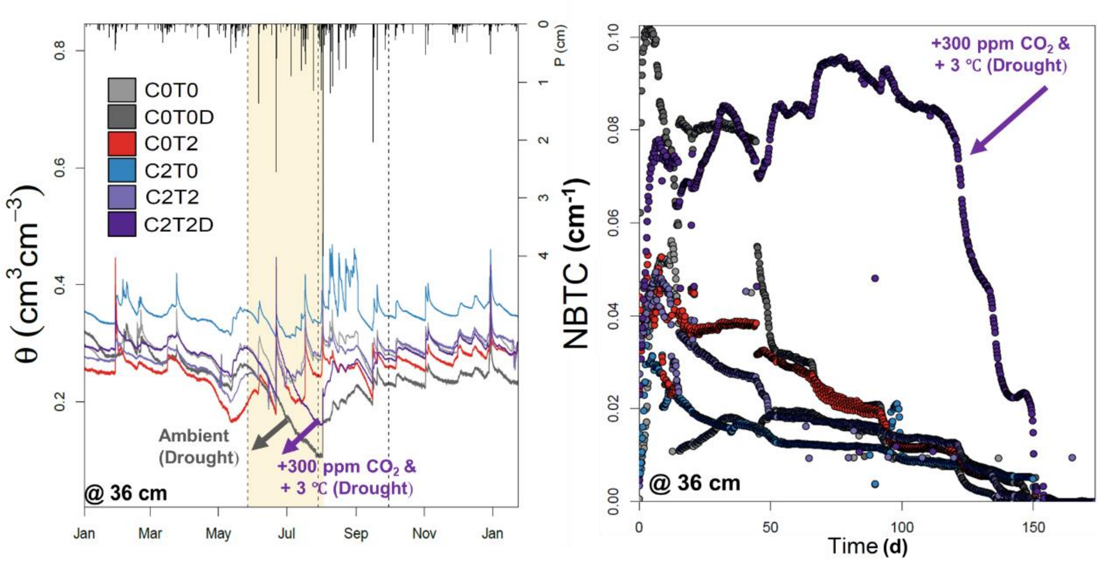

Figure A3. Here we show **left**) soil moisture at 36 cm (*n* = 1 per treatment) in the 2021 growing season and **right**) the post-label stable isotope signature of 36 cm soil water (*n* = 1 per treatment) normalized to the pre-label and label signature and volume or normalized breakthrough concentration (NBTC) in dimensions of L^{-1}.

2021 transpiration, bulk evapotranspiration, and soil water tracer signatures

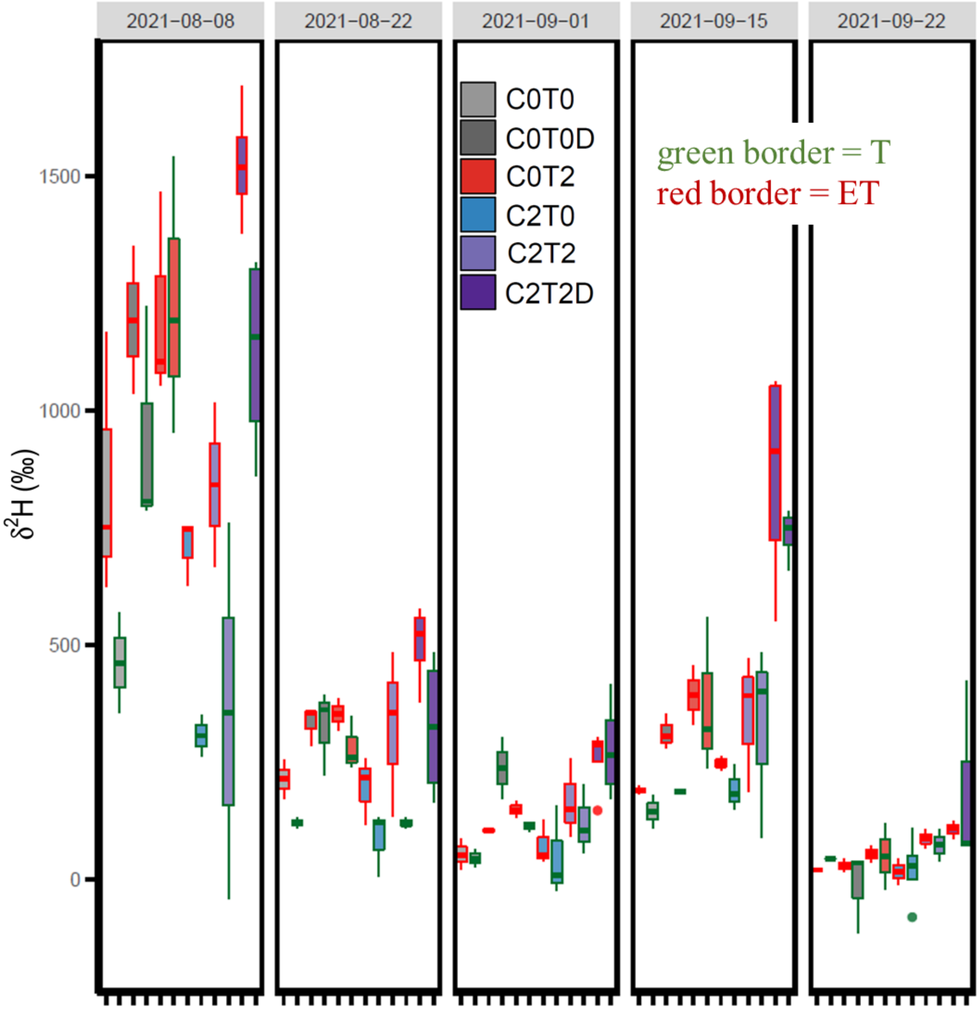

Figure A4. Deuterium signatures in canopy chamber-derived bulk evapotranspiration (with red borders) and leaf chamber-derived transpiration measurements. The above dataset follows the 2021 deuterium label applied in August of 2021 for 6 core treatments (C0T0: *n* = 4-6; C2T0: *n* = 3; C0T2: *n* = 3; C2T2: *n* = 3-4; C0T0D: *n* = 3-4, and C2T2D: *n* = 3-4). See **Figure 1** for treatment code description.

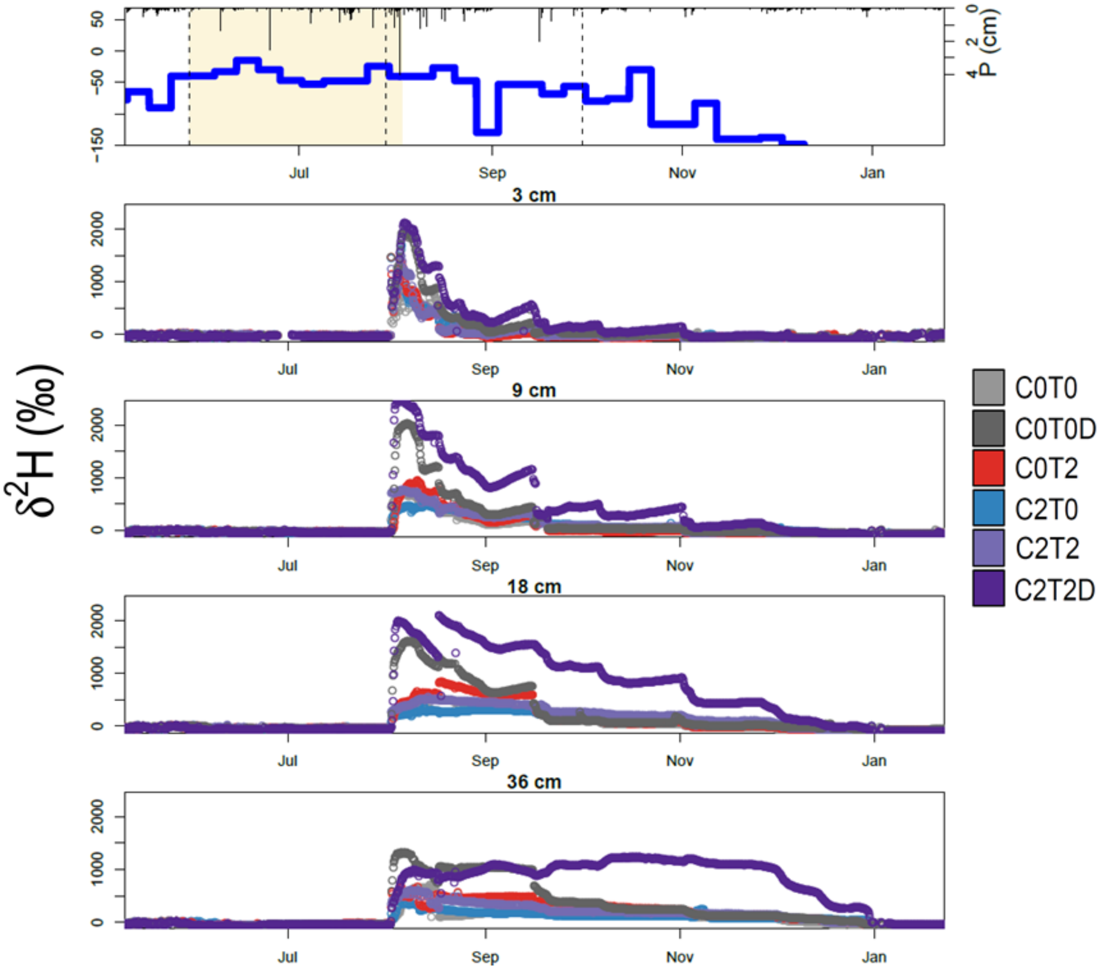

Figure A5. Deuterium signatures from precipitation (**top**) and soil pore water (**panels 2-5**) recorded in situ (4h) during the 2021 growing season. Note that the precipitation panel also displays hourly rainfall accumulation. See **Figure 1** for treatment code description.

Trying to discern transient from long-term alterations to soil hydraulic properties

In order to investigate the long-term effects of recurrent drought on soil properties, the annual field capacity was calculated using soil water content data. The method of computation was based on the approach described by Sumargo et al. (2021), which utilizes a robust algorithm to accurately assess the field capacity based on soil water content measurements. Through this analysis, we aimed to gain deeper insights into how recurrent drought impacts soil water storage and availability, which is crucial for understanding its implications for plant growth and crop yield. The results of the analysis revealed no significant changes in the field capacity of the soil, which is an indicator of the soil's ability to store water and support plant growth. This suggests that, despite recurrent drought conditions, the soil was still able to “reset” during winter. To conclude, no shift towards an alternative stable state of soil moisture, where the soil would experience a long-term change in water, was detected.

Take home messages:

- We did not find any long-term treatment effects on water storage/soil water retention in the soil during the winter months when analysing soil water content data.
- despite recurrent drought conditions, the soil was still able to “reset” during winter.
-

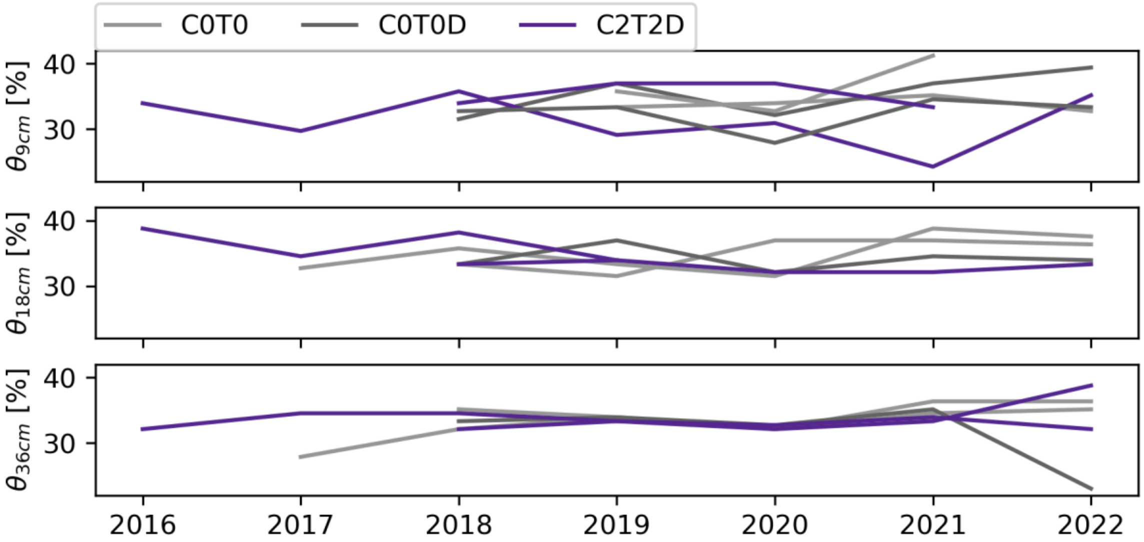

Figure A6. Annual winter field capacity estimated from field soil water content data at 9, 18, and 36cm depth.

Method description figure:

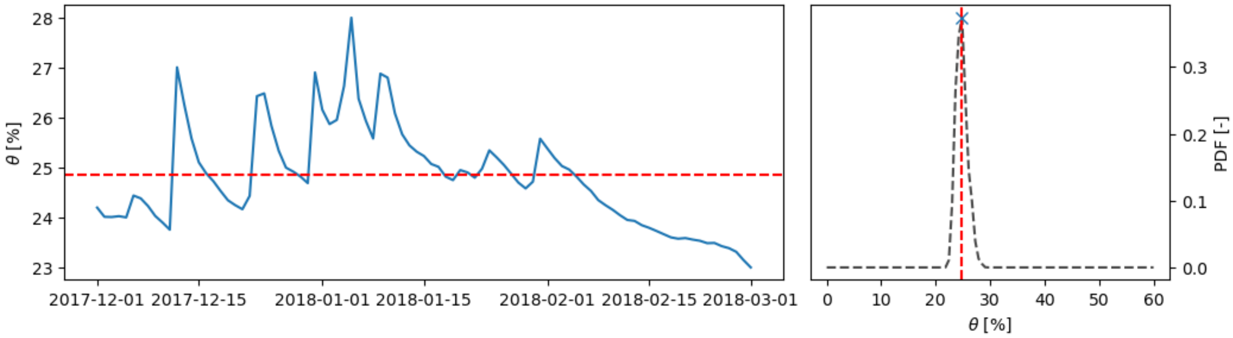

Figure A7. Estimated field capacity based on the probability density function of the measured soil water content data.

To further investigate the effects of drought on soil water retention, short-term drought effects were analyzed by comparing the estimated field capacity of the soil at the beginning of the year (i.e., in winter) with the field capacity after rewetting in the drought plots and at the end of the year (i.e., in winter again). The results showed that the field capacity of the soil was reduced after the drought, with the largest effect size observed in the future drought plots. In agreement with the findings from the previous section, the field capacity seemed to "reset" to pre-drought levels during the winter. However, a small decrease in the early winter field capacity was observed in 2020, which could be a result of the drought that occurred in the previous year. Nevertheless, the field capacity seemed to "reset" again during the 2020/2021 winter, indicating that the soil's ability to retain water may be relatively resilient to short-term drought events. These findings imply that the soil might have the capability to recover from drought in the short-term.

Take home messages:

- The greatest impact of natural dry spells on field capacity was seen in 2018 and 2019. This impact was similar for both C0T0 and C2T2. However, the overall impact was the highest at C2T2D. Additionally, it appears that the field capacity storage levels returned to normal during the winter.

Method description figure:

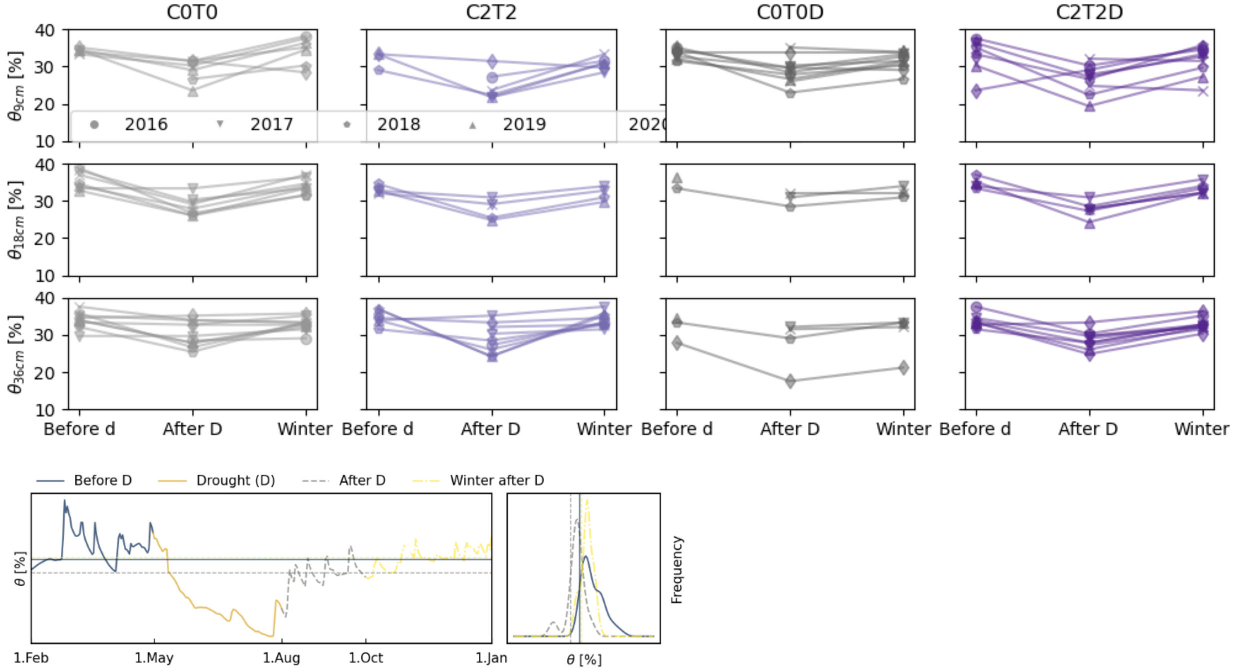

Figure A8. Estimated field capacity based on the probability density function of the measured soil water content data for three distinct periods (before the drought, period after the drought, two months after the drought).