

More extreme and frequent drought periods reduced crop production and altered stable isotope ratios of C and N in plants

Häufigere und extreme Trockenheit verringerte die Pflanzenproduktion und veränderte die Stabilisotopenverhältnisse von C und N in den Pflanzen

Andrea Watzinger^{1*}, Judith Prommer¹, Andreea Spiridon^{1,2}, Weronika Kisielinska¹, Rebecca Hood-Nowotny¹, Herbert Formayer³, Anna Wawra⁴, Johannes Hösch⁴, Julia Miloczki⁴

¹ Institute of Soil Research, Department of Forestry and Soil Sciences, University of Natural Resources and Life Sciences, Vienna (BOKU), Konrad-Lorenz-Straße 24, 3430 Tulln an der Donau, Austria

² Division of Terrestrial Ecosystem Research, Center of Microbiology and Environmental Systems Science, University of Vienna, Djerassiplatz 1, 1030 Vienna, Austria

³ Institute of Meteorology and Climatology, University of Natural Resources and Life Sciences, Vienna (BOKU), Gregor-Mendel-Straße 33, 1180 Vienna, Austria

⁴ Department for Soil Health and Plant Nutrition, Austrian Agency for Health and Food Safety (AGES), Spargelfeldstraße 191, 1220 Vienna, Austria

* Corresponding author: andrea.watzinger@boku.ac.at

Received: 14 July 2023, received in revised form: 29 August 2023, accepted: 30 August 2023

Summary

Climate change scenarios predict more frequent and intense drought periods for 2071–2100 in the most important and intensively used agricultural region of Austria, the Marchfeld. Current and predicted lower precipitation scenarios were simulated at a lysimeter station for 9 years. Plant biomass, nitrogen (N) and carbon (C) content, and $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of plant compartments were monitored in years 7–9. Aboveground biomass of cereals and grain yield decreased under the predicted scenario, while the quality of grain (% N) was unaffected. Weed and catch crops grown in winter were not affected or were even positively affected, possibly due to the accumulation of nutrients in the soil following the lower plant uptake in summer. Accordingly, low plant $\delta^{15}\text{N}$ values were mainly attributed to the presence of higher proportion of mineral fertilizer in the predicted precipitation scenario. As expected, water stress significantly increased $\delta^{13}\text{C}$ values in plants grown over summer, while this was not seen for plants growing over winter. Fertile agricultural soil might ameliorate but cannot outbalance the negative impact of more frequent and intense drought periods.

Keywords: plant production, drought, ^{13}C and ^{15}N isotopes, agroecosystem, Pannonian region

Zusammenfassung

Klimaszenarien prognostizieren für die Jahre 2071 bis 2100 häufigere und intensivere Dürreperioden in der wichtigsten und am intensivsten genutzten Agrarregion Österreichs, dem Marchfeld. In einer Lysimeterstation wurden 9 Jahre lang aktuelle und vorhergesagte Szenarien geringerer Niederschläge simuliert. Die Pflanzenbiomasse, Stickstoff- (N) und Kohlenstoffgehalt (C) sowie die $\delta^{13}\text{C}$ - und $\delta^{15}\text{N}$ -Werte der Pflanzenkompartimente wurden in den Jahren 7 bis 9 analysiert. Die oberirdische Biomasse von Getreide und der Ertrag gingen im vorhergesagten Szenario zurück, während die Qualität des Getreides (% N) unberührt blieb. Beikräuter und im Winter wachsende Zwischenfrüchte wurden nicht oder sogar positiv beeinflusst, was möglicherweise auf die Anreicherung von Nährstoffen im Boden aufgrund der geringeren Pflanzenaufnahme im Sommer zurückzuführen ist. Dementsprechend wurden niedrige $\delta^{15}\text{N}$ -Werte der Pflanzen hauptsächlich auf das Vorhandensein eines höheren Anteils an Mineraldünger im prognostizierten Niederschlagsszenario zurückgeführt. Wie erwartet, erhöhte der Wasserstress die $\delta^{13}\text{C}$ -Werte bei Pflanzen im Sommer signifikant, während dies im Winter nicht beobachtet wurde. Fruchtbare Böden können die negativen Auswirkungen häufigerer und intensiverer Dürreperioden abschwächen, jedoch nicht ausgleichen.

Schlagwörter: Pflanzenwachstum, Trockenheit, ^{13}C und ^{15}N Isotope, Agrarökosystem, pannonische Region

1. Introduction

Climate models predict an increase in average air temperatures, as well as a shift in precipitation patterns, resulting concurrently in more frequent and intense periods of heatwaves and drought in summer, accompanied by heavier intermittent rainfall events in Austria (APCC, 2014; IPCC, 2020; Thaler et al., 2021). A drought event encompasses a precipitation deficit, leading to soil water deficit, which exerts a range of stress effects on plants (Crocetti et al., 2020) and soil biota (Schimel, 2018).

The main water deficit response in plants is stomatal closure, thereby reducing photosynthetic CO_2 uptake and triggering photoinhibition (Huseynova et al., 2016; Ahmad et al., 2018). This leads to increased proportion of ^{13}C fixation, hence increasing the $\delta^{13}\text{C}$ values of plant tissues. Generally, plants discriminate against ^{13}C during carboxylation, and the observed isotope fractionation is positively correlated with the CO_2 intercellular partial pressure and negatively correlated with stomatal resistance and plant water-use efficiency (Farquhar et al., 1989). Differences in photosynthetic discrimination at the time of tissue development, relocation of C assimilates, and post-photosynthetic isotope fractionation lead to different $\delta^{13}\text{C}$ values in various plant tissues, with typically higher grain $\delta^{13}\text{C}$ values than those in straw (Craufurd et al., 1991).

Drought stress also hampers the uptake of nutrients, such as N, by plants due to impaired membrane functionality and internal transport leading to lower root absorbing capacity (Rathore et al., 2017; Ahmad et al., 2018). Water limitation and impaired photosynthesis induce the mobilization of reserves from the stem and leaves to the grain (Yang et al., 2003; Blum, 2005; Srivastava et al., 2017), whereby the translocation of proteins is favored over starch (Singh et al., 2012; Mariem et al., 2021). These changes cause reduced plant productivity and altered grain quality compared to those of plants with optimal water supply (Barnabás et al., 2008; Crocetti et al., 2020; Mariem et al., 2021).

Ultimately, drought can lead to severe yield losses, especially in rainfed summer crops (Eitzinger et al., 2013; Bodner et al., 2015; Thaler et al., 2021). Yield losses of 25%–38% in winter wheat, 40% in maize, and up to 50% in sugar beet and potatoes due to drought have been reported in southeastern Europe (Van Lanen et al., 2016; Nagy et al., 2018). Yield losses are more pronounced in soils with low water storage capacity, whereas soils rich in organic matter are deemed more resilient to extreme weather events, such as drought and heavy rainfall, due to their higher aggregate stability and higher water infiltration and storage capacities (Lal, 2004; Altieri et al., 2015).

The drought response patterns of plants and soil biota will reciprocally interact with soil carbon (C) and nitrogen (N) dynamics. During prolonged and more intense drought events, the ecosystem C cycle is likely to slow down due to lower plant C input and diminished plant residue mineralization (Wu et al., 2011). Considering the ecosystem N cycle, a reduction of plant N uptake and an accumulation of inorganic and organic N in the soil were reported (Deng et al., 2021). Accumulation of soil N under drought was also observed for this experimental site (Watzinger et al., 2023), possibly outbalancing the reduced nutrient uptake capacity of plants under drought. Croplands predominantly receive mineral N fertilizer with a distinct low $\delta^{15}\text{N}$ value, and $\delta^{15}\text{N}$ values in plants commonly reflect ^{15}N source signature (Choi et al., 2017). On the other hand, it is well documented that isotope fractionation processes in the soil and loss of ^{15}N depleted N compounds have increased $\delta^{15}\text{N}$ in plants under reduced mean annual precipitation in natural ecosystems (Amundson et al., 2003). Also, in agricultural settings, plant $\delta^{15}\text{N}$ can be driven by isotope fractionation processes in the soil (Watzka et al., 2006). In addition, $\delta^{15}\text{N}$ values in grain, in comparison to the values in straw, might give an indication of the plant availability of soil inorganic N at the time of grain filling. ^{15}N in grain is enriched if plants have to relocate N from leaves to the grain (Kanstrup et al., 2011; Zhou et al., 2013).

It is commonly agreed that the ecosystem resistance and resilience to drought increases with increasing biodiversity due to the asynchrony of species' responses (tolerance vs. recovery) (Klaus et al., 2016; Bardgett and Caruso, 2020). In croplands, particularly plant diversity is strongly reduced, leading to a decrease in the soil's C storage, the total nutrient pool (plant biomass and soil) (Furey and Tilman, 2021), and microbial activity (Lange et al., 2015). Often, long-term cultivated agricultural soils become impoverished in soil organic C content and exhibit a deterioration in soil structure under tillage. We, therefore, assumed very strong responses of crop yield and plant $\delta^{13}\text{C}$ values as a proxy of water use efficiency to more frequent and intense periods of drought. We also hypothesized that plant N content would increase and $\delta^{15}\text{N}$ values would decrease due to the accumulation of mineral fertilizer N in the soil under reduced precipitation.

To test this, main and catch crop yield, weed biomass, plant N and C content, and stable isotope values ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$) were monitored in three soil types of varying fertility in a lysimeter facility of the Pannonian region in Austria. The site had been exposed to current and predicted (for the period 2071–2100) precipitation regimes for 9 years. Results from the last three experimental years are presented here.

2. Materials and Methods

2.1. Experimental set-up

The Austrian Agency for Health and Food Safety (AGES) lysimeter facility consists of 18 filled gravitation lysimeters representing the three main soil types of the Marchfeld, namely, calcareous Phaeozem (Ps), calcic Chernozem (Ch), and gleyic Phaeozem (Pg) (Gerzabek and Krenn 2005; Stenitzer and Hösch, 2005). The gleyic Phaeozem, a groundwater-influenced soil type, had become dry and experienced unnatural shrinking and crack formation. The main soil chemical properties of the upper 10 cm of lysimeter soils were redetermined in 2019 and are presented in the Supplemental Table 1. Further soil properties can be found in Tataw et al. (2014) and Watzinger et al. (2023). Rainfall was simulated with an overhead irrigation system since 2011 (Tataw et al., 2014, 2016). For the “current” scenario, half of the lysimeters were irrigated according to current precipitation patterns, as calculated by the 30-year mean of rainfall (amount and distribution) in Groß-Enzersdorf, Marchfeld (517 mm). The other half of lysimeters in the “predicted” scenario were watered according to the precipitation pattern predicted for a dry year (20 percentile) for the period 2071–2100 in the Pannonian region (436 mm) (Tataw et al., 2016). From 2018 onward, an adapted and improved model, the historic (1961–2000) and the hot and dry model scenario presented in Seidl et al. (2019), was used to calculate the “current” scenario and the “predicted” very dry year (5 percentile) scenario (531 and 386 mm precipitation per annum, respectively) (Watzinger et al., 2023). The lysimeter station was covered by a plastic tunnel and irrigated during the growing season, and it remained uncovered in winter when it received ambient precipitation. The period of coverage and irrigation treatment followed the precipitation scenarios for dry (2017) and very dry (2018, 2019) years, except that a heavy rainfall event was simulated on the 25th of April

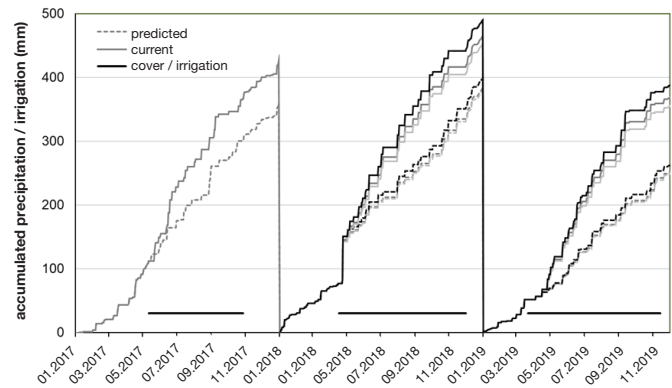


Figure 1. Period of cover/irrigation (black line) and precipitation and irrigation applied to the lysimeter soil from 2017 until 2019. From 2018 onward, the variation of irrigation – the minimum (light gray) and the maximum (black) on lysimeter replicates – besides the average (dark gray) irrigation is illustrated.

Abbildung 1. Folienabdeckung der Lysimeteranlage und Bewässerung (schwarze Linie) sowie die akkumulierte Niederschlags- und Bewässerungsmenge in den Jahren 2017, 2018 und 2019. Ab 2018 wurde die Schwankung - Minimum (hellgrau), Maximum (schwarz), Mittelwert (dunkelgrau) – der Lysimeterbewässerung dargestellt.

2018 and 60 mm of precipitation was applied additionally. The amounts of precipitation and irrigation applied in the years 2017–2019 are illustrated in Figure 1.

The crop rotation and crop residue management throughout the experiment followed the common agricultural practices in the Marchfeld region (Table 1). Before sowing and after the harvest, the soil was manually tilled. Fertilizer was applied according to Austrian standard recommendations (BML-FUW, 2017) (Table 2). N fertilizer was added as calcium ammonium nitrate (NAC 27 N, Borealis LAT GmbH, Austria) with a stable isotope composition $\delta^{15}\text{N}$ of -1.2‰ . Visual controls for pest infestations were done on a regular basis to identify potential insect pests and to allow for appropriate measures to be taken. No significant insect infestations were detected for the duration of the experiments described. However, weeds were quite abundant and were removed manually.

Table 1. Crop rotation and management of the lysimeters
Tabelle 1. Fruchtfolge und Bewirtschaftung der Lysimeteranlage

Crop	Sowing	Harvest	Crop residue management
Spring wheat (<i>Triticum turgidum</i> subsp. <i>durum</i> (Desf.) Husn) cv. Floradur	04.04.2017	20.07.2017	Crop residues removed
White mustard (<i>Sinapis alba</i> L.) catch crop	24.08.2017	07.03.2018	Mustard residues were mulched and incorporated into the soil on 09.04.2018
Spring barley (<i>Hordeum vulgare</i> L. cv. Cerbinetta)	09.04.2018	23.07.2018	Crop residues removed
Winter wheat (<i>Triticum aestivum</i> L.) cv. Capo	11.10.2018	03.07.2019	Crop residues incorporated

Table 2. Application rates of N fertilizer in kg N ha⁻¹ dependent on the soil type (calcaric Phaeozem - P_s; calcic Chernozem - Ch; gleyic Phaeozem - Pg)
Tabelle 2. Stickstoffdüngung in kg N ha⁻¹ angepasst an den Bodentyp (calcaric Phaeozem - P_s; calcic Chernozem - Ch; gleyic Phaeozem - Pg)

Fertilization date	Pg	P _s	Ch
04.04.2017	55	40	55
08.05.2018	50	50	50
20.03.2019	40	35	40
16.04.2019	65	45	65
16.05.2019	45	40	45

Aboveground plant biomass was harvested at the end of the vegetation period for crop and weed biomass determination and for further elemental and isotopic analyses in the laboratory. Plants were dried at 60°C for dry biomass determination. Cereal crops were separated into three different plant components – straw, grain, and chaff. On 06.07.2017, the second leaves after the flag leaves were sampled, pooled, and analyzed. Analysis of plant biomass and C and N isotope composition was conducted by Elemental Analyzer – Isotope Ratio Mass Spectrometry (EA-IRMS; elemental analyzer coupled to Delta V Advantage; Thermo Scientific, Bremen, Germany).

2.2. Statistical analysis

Two- or three-way analysis of variance (ANOVA) type III sum of squares analyses using soil type, precipitation treatment, and/or year as the main factors were run, and Tukey HSD (Honestly Significant Difference) tests were conducted. Generally, no transformation of raw data was necessary to

meet the assumptions of normality and variance homogeneity. For statistical analysis, the R package Jamovi was used (R Core team, 2020; The jamovi project, 2021, Gallucci, 2019).

3. Results and Discussion

3.1. Response of plant biomass production to drought

More frequent and intense drought periods significantly decreased the total biomass and grain yield of crops and the harvest index (proportion of grain biomass to total aboveground biomass) in our lysimeter experiment (Tables 3 and 4, Figure 2, Supplemental Figure 1, and Supplemental Table 2). Moreover, earlier plant maturation was observed under the predicted precipitation scenario. Grain yields were highest in the gleyic Phaeozem, followed by the calcic Chernozem and the sandy calcaric Phaeozem. However, the impact of drought was strongest in both Phaeozem soil types compared to Chernozem (40% vs. 30% biomass reduction in spring barley and 40% vs. 10% biomass reduction in winter wheat). The grain yield declined most strongly in the sandy Phaeozem (60% reduction). These results are in line with current knowledge of the response of cereals to water shortage as observed in our experiment. The soil water content in the upper 10 cm determined during several points throughout the vegetation periods frequently approached the wilting point (−1.5 MPa) (Watzinger et al., 2023). It has been repeatedly reported that water limitation during grain filling reduces photosynthesis and accelerates leaf senescence in cereals, resulting in reduced availability of assimilates and a shortening of the grain-filling period (Dupont and Altenbach, 2003; Barnabás et al., 2008; Mariem et al., 2021). The lack of photoassimilates as well

Table 3. Harvests of cultivated crops and weeds per plant species and year for the different soil types and precipitation treatments in g m⁻²

Tabelle 3. Ernteertrag (g m⁻²) von Getreide, Zwischenfrucht und Beikräutern aus den Jahren 2017, 2018 und 2019 für die verschiedenen Bodentypen und Niederschlagsszenarien

Crop (year)	Gleyic Phaeozem		Calcaric Phaeozem		Calcic Chernozem	
	Current	Predicted	Current	Predicted	Current	Predicted
Spring wheat (2017)	112 (19)	35 (4)	150 (38)	73 (56)	81 (19)	33 (30)
Mustard (2017–2018)	351 (38)	360 (43)	199 (63)	177 (17)	247 (88)	351 (81)
Spring barley (2018)	542 (56)	352 (56)	247 (104)	145 (122)	327 (68)	249 (44)
Weed (2018)	119 (47)	104 (53)	121 (36)	100 (40)	118 (88)	70 (27)
Winter wheat (2019)	953 (119)	562 (118)	456 (12)	242 (83)	625 (140)	564 (37)
Weed (2019)	12 (10)	6 (7)	33 (16)	3 (0)	35 (14)	8 (9)

Given are the average values (n = 3; standard deviation in brackets) of aboveground dry plant biomass.

Table 4. Two-way ANOVA table of the impact of soil and precipitation on the plant biomass of cash and catch crops, grain yield, and weeds in the years 2017–2019

Tabelle 4. 2-Wege-ANOVA-Tabelle zum Einfluss von Boden und Niederschlag auf die Pflanzenbiomasse von Haupt- und Zwischenfrüchten, Ertrag und Beikräuter für die Jahre 2017 bis 2019

Parameter	Unit	Soil		Precipitation	
		F	<i>p</i>	F	<i>p</i>
Spring wheat	g m ⁻²	4.47/P _s	0.035	19.6/curr	<0.001
- Grain	g m ⁻²	2.60	0.115	12.8/curr	0.004
- Straw	g m ⁻²	6.17/P _s	0.014	19.2/curr	<0.001
Mustard	g m ⁻²	12.0	0.001	1.14	0.306
Spring barley	g m ⁻²	12.4/Pg	0.001	8.76/curr	0.012
- Grain	g m ⁻²	12.2/Pg	0.001	8.73/curr	0.012
- Straw	g m ⁻²	4.09/Pg	0.044	6.97/curr	0.022
Weed	g m ⁻²	0.208	0.815	1.29	0.279
Winter wheat	g m ⁻²	18.6/Pg	<0.001	16.3/curr	0.002
- Grain	g m ⁻²	28.6/Pg	<0.001	27.6/curr	<0.001
- Straw	g m ⁻²	14.3/Pg	<0.001	9.15/curr	0.011
Weed	g m ⁻²	2.27	0.146	17.0/curr	0.001

F indicates the mean square of the treatment divided by the mean square of the residuals and *p* is the significance value. The treatment (soil and precipitation) with the higher value is indicated after F. Values with *p* ≤ 0.05 are highlighted in bold. Pg – gleyic Phaeozem; P_s – calcareic Phaeozem; Ch – calcic Chernozem; curr – current precipitation scenario; pre – predicted precipitation scenario;

as reduced activity of starch-synthesizing enzymes inhibit grain starch production, which is one of the leading causes of reduced crop yields under water deficit (Worch et al., 2011). Higher water-holding and nutrient provision capacity of Chernozem likely buffered the impact of drought, as already reported by Tataw et al. (2016). Formation of cracks in the gleyic Phaeozem, which has a comparable water holding capacity to Chernozem, enabled preferential water flow, and hence likely hindered the storage of water. Our results were well in accordance with those presented by Tataw et al. (2016) from the same experimental site, who found significant reduction of grain yield and harvest index.

In contrast to crops, weeds were less affected, which would underpin current knowledge that a genetically diverse community can adapt to environmental stress easier than a single species (Klaus et al., 2016) (Tables 3 and 4, Supplemental Table 2). Also, mustard biomass, which grows as a catch crop in winter, was not significantly affected by the soil type and precipitation scenarios. In contrast, the biomass of mustard even increased by 40% in Chernozem. It appeared that plants growing over the winter period (mustard and winter wheat) were not negatively affected by the previous drought periods when the current and predicted

precipitation manipulation treatments were not in place, that is, both treatments received the same amount of precipitation. Especially plants in the Chernozem even profited from this, which was also observed by Evans and Burke (2013). We suspect that nutrients in general and N specifically accumulated in the soil due to reduced plant uptake in late spring and summer. Accumulation of N under the predicted precipitation regime in this experimental site was indicated using a stable isotope labeling approach (Watzinger et al., 2023).

The variation of plant growth between the lysimeters was generally high due to variations within the irrigation system. This was caused by differences in the water pressure along the irrigation lines and the drizzlers (2018: current 464 ± 38 mm, predicted 383 ± 20 mm; 2019: current 401 ± 32 mm, predicted 284 ± 14 mm) (Figure 1). Moreover, replications of lysimeter × treatment combinations were low (*n* = 3). In addition, the intensity of irrigation was high (2017: 86.4 mm h⁻¹ and 2018 onward: 76.2 mm h⁻¹), mimicking rather extreme rainfall events with intermittent dry spells. Moreover, some lysimeters were affected by animal activities (bioturbation by mice, burrowing activities by rabbits, dogs, and crows), especially in 2017, and there was an island effect, as lysimeters were surrounded by bare soil. These experimental issues might have led to the observed high variability and lower plant growth than expected under comparable field conditions.

Our data has to be contextualized within the constraints of unaltered temperature and CO₂ concentration manipulation and bearing in mind that we had mimicked rather extreme drought years.

Cereal production models including temperature and CO₂ concentration, besides precipitation, simulated lower reduction of yield or even increased yield for the same region in an average climate change year: spring barley 2% to >10% and winter wheat 0%–10% reduction (Eitzinger et al., 2013); winter wheat around 10 % yield increase and spring barley 18%–21% (Alexandrov et al., 2002; Eitzinger et al., 2008); and winter wheat 18%–28% yield increase (Thaler et al., 2021). Yield increase was mainly attributed to CO₂ fertilization. Without CO₂ fertilization, the yield of winter wheat is expected to decrease by around 12% in 2080 (Eitzinger et al., 2008). In addition, the predicted precipitation pattern chosen for our lysimeter study simulated the driest year out of five (20 percentile) in 2017 and the driest year out of 20 (5 percentile) in 2019. Precipitation manipulation was only commenced during the growing season; thus, the predicted higher precipitation during winter season was

Table 5. Delta¹³C values of cultivated crops per plant species and year for the different soil types and precipitation treatments in ‰
Tabelle 5. Delta¹³C Werte der Kulturpflanzen pro Jahr für die verschiedenen Bodentypen und Niederschlagsszenarien in ‰

Crop (year)/part	Gleyic Phaeozem		Calcaric Phaeozem		Calcic Chernozem	
	Current	Predicted	Current	Predicted	Current	Predicted
Spring wheat (2017)/grain	−25.3 (0.6)	−23.6 (0.8)	−24.8 (0.8)	−23.7 (0.4)	−25.1 (1.0)	−24.4 (1.0)
Spring wheat (2017)/straw	−27.2 (1.0)	−26.0 (0.3)	−26.9 (0.3)	−26.0 (0.4)	−26.5 (0.6)	−25.5 (0.3)
Spring barley (2018)/grain	−27.1 (0.2)	−26.0 (0.3)	−25.2 (1.0)	−24.6 (0.7)	−27.9 (0.4)	−27.5 (0.3)
Spring barley (2018)/straw	n.d.	n.d.	−26.5 (0.3)	−25.7 (0.2)	−28.0 (0.3)	−27.1 (0.1)
Winter wheat (2019)/grain	−26.4 (0.1)	−24.6 (0.1)	−24.4 (0.1)	−23.6 (0.9)	−26.9 (0.8)	−25.1 (0.0)
Winter wheat (2019)/straw	−28.3 (0.8)	−27.5 (0.4)	−27.6 (0.5)	−26.7 (0.3)	−28.2 (0.4)	−27.6 (0.6)

Given are the average values ($n = 3$; standard deviation in brackets) n.d. not determined

dismissed in our experimental set-up. Thaler et al. (2021) have presented data from the 10 percentiles and found that the increase of yield was less pronounced (11%–23%).

3.2. Alteration of the plant $\delta^{13}\text{C}$ value

The increase of plant $\delta^{13}\text{C}$ in the predicted precipitation scenario verified increased stomatal resistance and reduced photosynthetic C assimilation (Table 5, Supplemental Tables 2–5). Delta ^{13}C values were also higher in sandy Phaeozem, followed by gleyic Phaeozem and Chernozem, which was also likely related to the soil water-holding capacity. Straw $\delta^{13}\text{C}$ val-

ues were in line with those reported for leaves by Tataw et al. (2016) on the same experimental site. $\delta^{13}\text{C}$ values were generally higher in grain than in leaves as reported earlier (Craufurd et al., 1991). The difference between straw and grain $\delta^{13}\text{C}$ values was only significantly affected by the year/crop species. The difference was highest in winter wheat in 2019 (up to 3‰) and lowest in spring barley in 2018. This difference might have either derived from physiological differences of the plant species (Domergue et al., 2022) or be explained by a higher difference in water availability during leaf and grain development in 2019 than in 2018, when plants had received an additional 60-mm heavy rainfall event in late April.

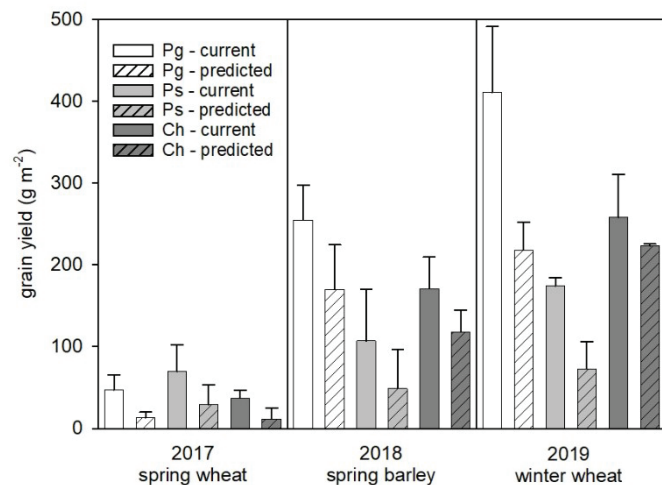


Figure 2. Grain yield of spring wheat (2017), spring barley (2018), and winter wheat (2019) for the different soil types and precipitation treatments in g m^{-2} . Given are the arithmetic mean values ($n = 3$), and the error bars represent the standard deviation.

Abbildung 2. Ertrag von Sommerweizen (2017), Sommergerste (2018) und Winterweizen (2019) für die verschiedenen Bodentypen und Niederschlagsszenarien in g m^{-2} . Gegeben sind die arithmetischen Mittelwerte ($n=3$) und die Standardabweichung als Fehlerbalken.

3.3. The plant N content and its delta¹⁵N values

Grain N content of spring wheat was significantly elevated under drought in 2017. In the following years, the N content did not change significantly between the current and predicted precipitation scenarios, indicating no loss in the quality of grain (Supplemental Tables 2–5 and Supplemental Figure 2). Most importantly, N content in straw and mustard was higher under drought, which was likely driven by an accumulation of available N in the soil system due to lower plant N uptake, while N fertilization remained unchanged and N mineralization was less reduced (Watzinger et al., 2023, Evans and Burke, 2013) (Supplemental Tables 2–5 and Supplemental Figure 3). Higher straw N content likely facilitated the translocation of N into grains. In addition, the mobilization and translocation of proteins to cereal grains over the translocation of starch is favored under drought stress (Mariem et al., 2021), which might have also come into play in our experiment, thus balancing the grain quality between the treatments.

Crop $\delta^{15}\text{N}$ values were significantly elevated in gleyic Phaeozem and Chernozem in comparison to the sandy calcaric

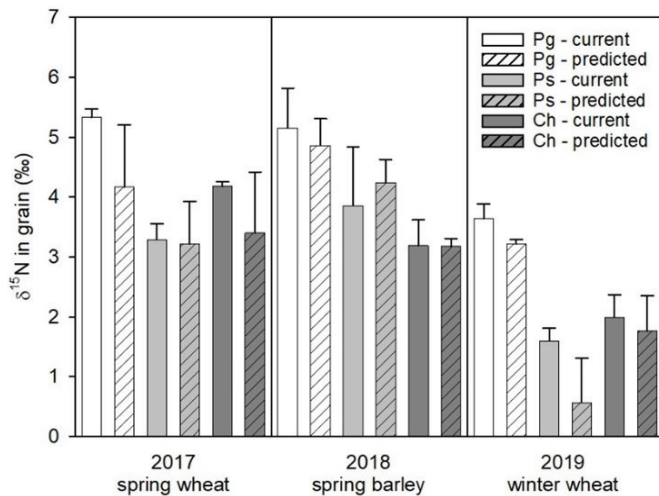


Figure 3. Grain $\delta^{15}\text{N}$ values of spring wheat (2017), spring barley (2018), and winter wheat (2019) for the different soil types and precipitation treatments in ‰. Given are arithmetic mean values ($n = 3$), and the error bars represent the standard deviation.

Abbildung 3. Korn $\delta^{15}\text{N}$ Werte von Sommerweizen (2017), Sommergerste (2018) und Winterweizen (2019) für die verschiedenen Bodentypen und Niederschlagszenarien in ‰. Gegeben sind die arithmetischen Mittelwerte ($n = 3$) und die Standardabweichung als Fehlerbalken.

Phaeozem soil, with a significant decrease in 2019 (Figure 3, Supplemental Tables 2 and 4 and Supplemental Figure 4). This likely resulted from a higher N uptake in the Pg and Ch soil and the higher percentage uptake of soil-born N with a higher $\delta^{15}\text{N}$ value (6.9‰) than mineral N fertilizer (−1.2‰). Plant $\delta^{15}\text{N}$ decreased in 2019, which can be attributed to three applications of N fertilizer in comparison to only one fertilization event in the previous years. Grain was ^{15}N enriched by around 1‰ in comparison to straw. Enrichments are related to relocation of N from leaf to grain during grain filling (Kanstrup et al., 2011; Zhou et al., 2013), while provision of mineral N fertilizer during grain filling leads to lower fractionation due to lower relocation of N (Fuertes-Mendizábal et al., 2018). Accordingly, ^{15}N enrichment in grain was less in winter wheat, which received three applications of mineral N fertilizer, in contrast to only one mineral fertilizer application in April and May during spike formation in spring wheat and spring barley in 2017 and 2018. Significant differences in plant $\delta^{15}\text{N}$ values between precipitation scenarios were rare and observed in leaves in 2017 and grain in 2019. Then, $\delta^{15}\text{N}$ values were lower under drought, possibly indicating higher percentage of mineral fertilizer N usage (Bol et al., 2005; Choi et al., 2017) and higher N remaining from soybean plant residues (N-fixing

plant species with low $\delta^{15}\text{N}$ values) incorporated in 2016. Decreased plant $\delta^{15}\text{N}$ values have also been attributed to more closed N cycling, that is, low N input/output versus N turnover in soils. A closer N cycle has been seen in natural ecosystems and increasing mean annual precipitation (Amundson et al., 2003), while the use of mineral fertilizer might trigger the loss of N under drought due to asynchronicity of fertilizer application and plant uptake (Ullah et al., 2020). However, as we have already documented lower soil N losses but similar N turnover rates under drought in this experiment (Watzinger et al., 2023), we concluded that $\delta^{15}\text{N}$ values in the plant were rather driven by the source coinciding with the accumulation of mineral N fertilizer.

4. Conclusions

The study area “Marchfeld” is one of the warmest and driest areas (precipitation: 560 mm year^{−1}, mean annual temperature: 11.2°C) in Austria and is intensively used for agricultural production of grain and vegetables. Especially for enabling the cultivation of vegetables, irrigation is conducted, and in the last few years also, cereals had to be occasionally irrigated in spring. The 9-year lasting precipitation manipulation in our experiment affected aboveground biomass (crops) due to drought stress more than soil biota (Watzinger et al., 2023), reinforcing the dominant role of plants in controlling the soil C and N cycles via N uptake and C input. Higher biomass production in the soil type with higher water storage capacity corroborates the importance of good soil structure, but fertile soils cannot completely outbalance the negative impacts due to more frequent and intense drought periods. Regarding the predicted extreme weather events, additional water conservation strategies will become very important. In addition, fertilization regimes might need to be adapted to prevent the accumulation of nutrients in the soil system under reduced plant biomass growth. N, in particular, is prone to gaseous and hydrological losses in the ecosystem, when fields are irrigated in the near future.

Acknowledgments

The work was funded by the Austrian Climate Research Program 9 under the project name Climagrocycle (KR16AC0K13275).

References

- Ahmad, Z., Waraich, E.A., Akhtar, S., Anjum, S., Ahmad, T., Mahboob, W., Hafeez, O.B.A., Tapera, T., Labuschagne, M., Rizwan, M., 2018. Physiological responses of wheat to drought stress and its mitigation approaches. *Acta Physiologiae Plantarum* 40, 80.
- Alexandrov, V., Eitzinger, J., Cajic, V., Oberforster, M., 2002. Potential impact of climate change on selected agricultural crops in north-eastern Austria. *Global Change Biology* 8, 372–389.
- Altieri, M.A., Nicholls, C.I., Henao, A., Lana, M.A., 2015. Agroecology and the design of climate change-resilient farming systems. *Agronomy for Sustainable Development* 35, 869–890.
- Amundson, R., Austin, A.T., Schuur, E.A.G., Yoo, K., Matzek, V., Kendall, C., Uebersax, A., Brenner, D., Baisden, W.T., 2003. Global patterns of the isotopic composition of soil and plant nitrogen. *Global Biogeochemical Cycles* 17, 1031.
- APCC, 2014. Austrian Assessment Report 2014 (AAR14). Verlag der Österreichischen Akademie der Wissenschaften, Wien.
- Bardgett, R.D., Caruso, T., 2020. Soil microbial community responses to climate extremes: Resistance, resilience and transitions to alternative states. *Philosophical Transactions of the Royal Society B: Biological Sciences* 375, 1794.
- Barnabás, B., Jäger, K., Fehér, A., 2008. The effect of drought and heat stress on reproductive processes in cereals. *Plant, Cell and Environment* 31, 11–38.
- Blum, A., 2005. Drought resistance, water-use efficiency, and yield potential - Are they compatible, dissonant, or mutually exclusive? *Australian Journal of Agricultural Research* 56, 1159–1168.
- BMLFUW, 2017. Richtlinie Für Die Interpretation Von Bodenuntersuchungs- Ergebnissen in Der. Bundesministerium Für Land- Und Forstwirtschaft, Umwelt Und Wasserwirtschaft 117.
- Bodner, G., Nakhforoosh, A., Kaul, H.P., 2015. Management of crop water under drought: a review. *Agronomy for Sustainable Development* 35, 401–442.
- Bol, R., Eriksen, J., Smith, P., Garnett, M.H., Coleman, K., Christensen, B.T., 2005. The natural abundance of ^{13}C , ^{15}N , ^{34}S and ^{14}C in archived (1923–2000) plant and soil samples from the Askov long-term experiments on animal manure and mineral fertilizer. *Rapid Communications in Mass Spectrometry* 19, 3216–3226.
- Choi, W.J., Kwak, J.H., Lim, S.S., Park, H.J., Chang, S.X., Lee, S.M., Arshad, M.A., Yun, S.I., Kim, H.Y., 2017. Synthetic fertilizer and livestock manure differently affect $\delta^{15}\text{N}$ in the agricultural landscape: A review. *Agriculture, Ecosystems and Environment* 237, 1–15.
- Craufurd, P.Q., Austin, R.B., Acevedo, E., Hall, M.A., 1991. Carbon isotope discrimination and grain-yield in barley. *Field Crops Research* 27, 301–313.
- Crocetti, L., Forkel, M., Fischer, M., Jurečka, F., Grlj, A., Salentinig, A., Trnka, M., Anderson, M., Ng, W.T., Kokalj, Ž., Bucur, A., Dorigo, W., 2020. Earth Observation for agricultural drought monitoring in the Pannonian Basin (southeastern Europe): current state and future directions. *Regional Environmental Change* 20, 123.
- Deng, L., Peng, C., Kim, D.G., Li, J., Liu, Y., Hai, X., Liu, Q., Huang, C., Shangguan, Z., Kuzyakov, Y., 2021. Drought effects on soil carbon and nitrogen dynamics in global natural ecosystems. *Earth-Science Reviews* 214, 103501.
- Domergue, J.B., Abadie, C., Lalande, J., Deswarte, J.C., Ober, E., Laurent, V., Zimmerli, C., Lerebour, P., Duchalais, L., Bédard, C., Derory, J., Moittie, T., Lamothe-Sibold, M., Beauchêne, K., Limami, A.M., Tcherkez, G., 2022. Grain carbon isotope composition is a marker for allocation and harvest index in wheat. *Plant Cell and Environment* 45, 2145–2157.
- Dupont, F.M., Altenbach, S.B., 2003. Molecular and biochemical impacts of environmental factors on wheat grain development and protein synthesis. *Journal of Cereal Science* 38, 133–146.
- Eitzinger, J., Formayer, H., Thaler, S., Trnka, M., Zdenek, Z., Alexandrov, V., 2008. Aspects on results and uncertainties of climate change impact simulation studies for agricultural crop production in Europe. *Bodenkultur* 59, 131–147.
- Eitzinger, J., Trnka, M., Semerádová, D., Thaler, S., Svobodová, E., Hlavinka, P., Šiška, B., Takáč, J., Malatiniská, L., Nováková, M., Dubrovský, M., Žalud, Z., 2013. Regional climate change impacts on agricultural crop production in Central and Eastern Europe - Hotspots, regional differences and common trends. *Journal of Agricultural Science* 151, 787–812.
- Evans, S.E., Burke, I.C., 2013. Carbon and Nitrogen Decoupling Under an 11-Year Drought in the Shortgrass Steppe. *Ecosystems* 16, 20–33.
- Fuertes-Mendizábal, T., Estavillo, J.M., Duñabeitia, M.K., Huérfano, X., Castellón, A., González-Murua, C., Aizpuru, A., González-Moro, M.B., 2018. ^{15}N natural abundance evidences a better use of n sources by late nitrogen

- application in bread wheat. *Frontiers in Plant Science* 9, 1–11.
- Furey, G.N., Tilman, D., 2021. Plant biodiversity and the regeneration of soil fertility. *Proceedings of the National Academy of Sciences of the United States of America* 118, 1–8.
- Huseynova, I.M., Rustamova, S.M., Suleymanov, S.Y., Aliyeva, D.R., Mammadov, A.C., Aliyev, J.A., 2016. Drought-induced changes in photosynthetic apparatus and antioxidant components of wheat (*Triticum durum* Desf.) varieties. *Photosynthesis Research* 130, 215–223.
- Gerzabek, M.H., Krenn, A., 1996. Errichtung der Lysimeteranlage Hirschstetten. In: Bundesamt für Alpenländische Landwirtschaft (Hrsg.): 6. Gumpensteiner Lysimetertagung, 33–36, 16.–17.4.1996, Gumpenstein.
- IPCC, 2020. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.
- Kanstrup, M., Thomsen, I.K., Andersen, A.J., Bogaard, A., Christensen, B.T., 2011. Abundance of ^{13}C and ^{15}N in emmer, spelt and naked barley grown on differently manured soils: Towards a method for identifying past manuring practice. *Rapid Communications in Mass Spectrometry* 25, 2879–2887.
- Klaus, V.H., Hölzel, N., Prati, D., Schmitt, B., Schöning, I., Schrumpf, M., Solly, E.F., Hänsel, F., Fischer, M., Kleinebecker, T., 2016. Plant diversity moderates drought stress in grasslands: Implications from a large real-world study on ^{13}C natural abundances. *Science of the Total Environment* 566–567, 215–222.
- Lal, R., 2004. Soil carbon sequestration impacts on global climate change and food security. *Science* 304, 1623–1627.
- Lange, M., Eisenhauer, N., Sierra, C.A., Bessler, H., Engels, C., Griffiths, R.I., Mellado-Vázquez, P.G., Malik, A.A., Roy, J., Scheu, S., Steinbeiss, S., Thomson, B.C., Trumbore, S.E., Gleixner, G., 2015. Plant diversity increases soil microbial activity and soil carbon storage. *Nature Communications* 6, 6707.
- Mariem, S. Ben, Soba, D., Zhou, B., Loladze, I., Morales, F., Aranjuelo, I., 2021. Climate Change, Crop Yields, and Grain Quality of C3 Cereals: A Meta-Analysis of $[\text{CO}_2]$, Temperature, and Drought Effects. *Plants* 10, 1052.
- Nagy, A., Fehér, J., Tamás, J., 2018. Wheat and maize yield forecasting for the Tisza river catchment using MODIS NDVI time series and reported crop statistics. *Computers and Electronics in Agriculture* 151, 41–49.
- Rathore, V.S., Nathawat, N.S., Bhardwaj, S., Sasidharan, R.P., Yadav, B.M., Kumar, M., Santra, P., Yadava, N.D., Yadav, O.P., 2017. Yield, water and nitrogen use efficiencies of sprinkler irrigated wheat grown under different irrigation and nitrogen levels in an arid region. *Agricultural Water Management* 187, 232–245.
- Seidl, R., Albrich, K., Erb, K., Formayer, H., Leidinger, D., Leitinger, G., Tappeiner, U., Tasser, E., Rammer, W., 2019. What drives the future supply of regulating ecosystem services in a mountain forest landscape? *Forest Ecology and Management* 445, 37–47.
- Singh, S., Gupta, A.K., Kaur, N., 2012. Influence of drought and sowing time on protein composition, antinutrients, and mineral contents of wheat. *The Scientific World Journal* 2012, 485751.
- Srivastava, A., Srivastava, P., Sharma, A., Sarlach, R.S., Bains, N.S., 2017. Effect of stem reserve mobilization on grain filling under drought stress conditions in recombinant inbred population of wheat. *Journal of Applied and Natural Science* 9, 1–5.
- Stenitzer, E., Hösch, J., 2005. Grundwasserneubildung im Marchfeld – Lysimetermessungen und Modellrechnungen, in: Tagungsband Der 11. Gumpensteiner Lysimetertagung “Lysimetrie Im Netzwerk Der Dynamik von Ökosystemen.” pp. 41–44.
- Tataw, J.T., Baier, F., Krottenthaler, F., Pachler, B., Schwaiger, E., Wyhlidal, S., Formayer, H., Hösch, J., Baumgarten, A., Zaller, J.G., 2016. Climate change induced rainfall patterns affect wheat productivity and agroecosystem functioning dependent on soil types. *Ecological Research* 31, 203–212.
- Tataw, J.T., Hall, R., Ziss, E., Schwarz, T., Von Hohenberg Und Buchwald, C., Formayer, H., Hösch, J., Baumgarten, A., Berthold, H., Michel, K., Zaller, J.G., 2014. Soil types will alter the response of arable agroecosystems to future rainfall patterns. *Annals of Applied Biology* 164, 35–45.
- Thaler, S., Formayer, H., Kubu, G., Trnka, M., Eitzinger, J., 2021. Effects of bias-corrected regional climate projections and their spatial resolutions on crop model results under different climatic and soil conditions in Austria. *Agriculture (Switzerland)* 11, 1–39.
- Ullah, M.R., Corneo, P.E., Dijkstra, F.A., 2020. Inter-seasonal Nitrogen Loss with Drought Depends on Fertilizer Management in a Seminal Australian Grassland. *Ecosystems* 23, 1281–1293.
- Van Lanen, H.A.J., Laaha, G., Kingston, D.G., Gauster, T., Ionita, M., Vidal, J.P., Vlnas, R., Tallaksen, L.M., Stahl, K., Hannaford, J., Delus, C., Fendekova, M., Mediero,

- L., Prudhomme, C., Rets, E., Romanowicz, R.J., Gaillez, S., Wong, W.K., Adler, M.J., Blauhut, V., Caillouet, L., Chelcea, S., Frolova, N., Gudmundsson, L., Hanel, M., Haslinger, K., Kireeva, M., Osuch, M., Sauquet, E., Stagge, J.H., Van Loon, A.F., 2016. Hydrology needed to manage droughts: the 2015 European case. *Hydrological Processes* 30, 3097–3104.
- Watzinger, A., Prommer, J., Spiridon, A., Kisielinska, W., Hood-Nowotny, R., Leitner, S., Wanek, W., Resch, C., Heilig, M., Murer, E., Formayer, H., Wawra, A., Miloczki, J., 2023. Functional redundant soil fauna and microbial groups and processes were fairly resistant to drought in an agroecosystem. *Biology and Fertility of Soils* 59, 629–641.
- Watzka, M., Buchgraber, K., Wanek, W., 2006. Natural ^{15}N abundance of plants and soils under different management practices in a montane grassland. *Soil Biology and Biochemistry* 38, 1564–1576.
- Worch, S., Rajesh, K., Harshavardhan, V.T., Pietsch, C., Korzun, V., Kuntze, L., Börner, A., Wobus, U., Röder, M.S., Sreenivasulu, N., 2011. Haplotyping, linkage mapping and expression analysis of barley genes regulated by terminal drought stress influencing seed quality. *BMC Plant Biology* 11, 1–14.
- Wu, Z., Dijkstra, P., Koch, G.W., Peñuelas, J., Hungate, B.A., 2011. Responses of terrestrial ecosystems to temperature and precipitation change: A meta-analysis of experimental manipulation. *Global Change Biology* 17, 927–942.
- Yang, J.C., Zhang, J.H., Wang, Z.Q., Zhu, Q.S., Liu, L.J., 2003. Involvement of abscisic acid and cytokinins in the senescence and remobilization of carbon reserves in wheat subjected to water stress during grain filling. *Plant, Cell and Environment* 26, 1621–1631.
- Zhou, W., Hu, C.S., Li, J., Christie, P., He, X.H., Ju, X.T., 2013. Natural ^{15}N Abundance in Winter Wheat Amended with Urea and Compost: A Long-Term Experiment. *Pedosphere* 23, 835–843.

Supplemental Tables and Figures

Supplemental Table 1. Chemical and physical soil characteristics ($n = 6$) of gleyic Phaeozem (Pg), sandy calcaric Phaeozem (P_s), and calcic Chernozem (Ch) in the upper 10 cm.

Ergänzungstabelle 1. Chemische und physikalische Bodeneigenschaften ($n = 6$) des gleyic Phaeozem (Pg), des sandigen calcaric Phaeozem (P_s) und des calcic Chernozem (Ch) in den oberen 10 cm.

Parameter	Pg	Ps	Ch
pH	7.92 ± 0.04	7.93 ± 0.03	7.94 ± 0.03
CaCO ₃ (%)	29.0 ± 1.0	13.9 ± 0.4	20.9 ± 1.0
Total organic C (%)	2.32 ± 0.09	1.93 ± 0.12	2.91 ± 0.04
Total N (%)	0.211 ± 0.012	0.102 ± 0.005	0.227 ± 0.005
Available N (mg/kg/7 d)	57.9 ± 5.7	37.5 ± 5.5	59.2 ± 4.5
Available P (mg/kg)	62.5 ± 5.2	134.3 ± 3.8	81.0 ± 6.2
Available K (mg/kg)	82.02 ± 13.5	57.0 ± 8.5	73.5 ± 8.0
CEC (cmolc/kg)	25.9 ± 1.2	13.8 ± 0.4	28.9 ± 0.3
Ca (% from CEC)	76.5 ± 1.4	78.1 ± 0.7	78.4 ± 1.0
Mg (% from CEC)	19.8 ± 1.2	18.0 ± 0.6	18.6 ± 0.9
K (% from CEC)	1.1 ± 0.1	1.5 ± 0.2	0.9 ± 0.1
Na (% from CEC)	2.5 ± 0.4	2.4 ± 0.4	2.1 ± 0.3
Aggregate stability (%)	21.3 ± 5.5	23.2 ± 8.5	30.7 ± 6.8

Available N determined using anaerobic incubation (ÖNORM L1204); Available K and P determined using a calcium lactate acetate extraction; CEC = cation exchange capacity determined using BaCl₂ extraction; H, Mn, Fe, and Al were not detected in the BaCl₂ extractant.

Supplemental Table 2. Three-way ANOVA tables of the overall impact of soil, precipitation, and year (2017, 2018, and 2019) on crop yield, carbon and nitrogen content, and carbon and nitrogen isotope signature

Ergänzungstabelle 2. 3-Wege-ANOVA-Tabellen der Auswirkungen von Boden, Niederschlag und Jahr (2017, 2018 und 2019) auf Ernteertrag, Kohlenstoff- und Stickstoffgehalt sowie Kohlenstoff- und Stickstoffisotopensignatur.

Parameter	Unit	Soil		Precipitation		Year
		F	p	F	p	p
Crop	g m ⁻²	25.8/Pg, Ch	<0.001	34.1/curr	<0.001	<0.001
- Grain	g m ⁻²	30.9/Pg, Ch	<0.001	42.9/curr	<0.001	<0.001
- Straw	g m ⁻²	16.4/Pg	<0.001	20.5/curr	<0.001	<0.001
Harvest index		2.004	0.150	7.98/curr	0.008	0.031
Weed**	g m ⁻²	0.08	0.924	3.75	0.065	<0.001
Grain N	%	0.76	0.474	0.60	0.444	0.005
Straw N*	%	0.79	0.461	12.3/pre	0.001	<0.001
Grain δ ¹⁵ N	‰	40.3/Pg	<0.001	6.09/curr	0.019	<0.001
Straw δ ¹⁵ N*	‰	11.0/Ch	<0.001	0.16	0.688	<0.001
Grain C	%	4.19/P _s , Ch	0.024	0.248	0.662	0.061
Straw C*	%	5.94/P _s	0.006	0.50	0.485	<0.001
Grain δ ¹³ C	‰	28.4/P _s	<0.001	33.8/pre	<0.001	<0.001
Straw δ ¹³ C*	‰	10.2/P _s	<0.001	38.7/pre	<0.001	<0.001

F indicates the mean square of the treatment divided by the mean square of the residuals and p is the significance value. The treatment (soil and precipitation) with the higher value is indicated after F. Values with $p \leq 0.05$ are highlighted in bold. *Pg not determined in 2018; **not collected in 2017; Pg – gleyic Phaeozem; P_s – sandy Phaeozem; Ch – Chernozem; curr – current precipitation scenario; pre – predicted precipitation scenario

Supplemental Table 3. Two-way ANOVA table of the impact of soil and precipitation on carbon and nitrogen content and isotope signature of spring wheat and mustard cultivated in 2017

Ergänzungstabelle 3. 2-Wege-ANOVA-Tabelle zum Einfluss von Boden und Niederschlag auf den Kohlenstoff- und Stickstoffgehalt und die Isotopensignatur von Sommerweizen und Senf (2017)

Parameter	Unit	Soil		Precipitation	
		F	<i>p</i>	F	<i>p</i>
Spring wheat – harvest 20.07.2017					
Grain N	%	16.8/Pg, Ch	<0.001	5.11/pre	0.043
Straw N	%	13.4/Pg, Ch	<0.001	9.65/pre	0.009
Grain δ ¹⁵ N	‰	7.61/Pg	0.007	4.46	0.056
Straw δ ¹⁵ N	‰	10.1/Pg, Ch	0.003	2.78	0.121
Grain C	%	8.11/Pg, Ch	0.006	0.61	0.450
Straw C	%	4.49	0.035	0.71	0.416
Grain δ ¹³ C	‰	0.61	0.561	8.83/pre	0.012
Straw δ ¹³ C	‰	2.16	0.158	15.2/pre	0.002
Spring wheat – leaf 06.07.2017					
Leaf N	%	19.0/Pg, Ch	<0.001	5.11/pre	0.043
Leaf δ ¹⁵ N	‰	8.96/Pg	0.004	14.0/curr	0.003
Leaf C	%	0.088	0.916	3.97	0.070
Leaf δ ¹³ C	‰	2.13	0.161	30.8/pre	<0.001
Mustard leaf 24.10.2017					
Mustard N	%	41.3/Pg	<0.001	17.1/pre	0.003
Mustard δ ¹⁵ N	‰	0.52	0.609	1.52	0.241
Mustard C	%	3.59	0.063	4.50	0.057
Mustard δ ¹³ C	‰	0.65	0.538	4.18	0.064

F indicates the mean square of the treatment divided by the mean square of the residuals and *p* is the significance value. The treatment (soil and precipitation) with the higher value is indicated after F. Values with $p \leq 0.05$ are highlighted in bold. Pg – gleyic Phaeozem; P_s – sandy Phaeozem; Ch – Chernozem; curr – current precipitation scenario; pre – predicted precipitation scenario

Supplemental Table 4: Two-way ANOVA tables of the impact of soil and precipitation on yield, carbon and nitrogen content, and isotope signature of spring barley cultivated in 2018

Ergänzungstabelle 4. 2-Wege-ANOVA-Tabelle zum Einfluss von Boden und Niederschlag auf den Kohlenstoff- und Stickstoffgehalt und die Isotopensignatur von Sommergerste (2018)

Spring barley – harvest 23.07.2018					
Parameter	Unit	Soil		Precipitation	
		F	<i>p</i>	F	<i>p</i>
Grain N	%	0.24	0.792	3.11	0.103
Straw N*	%	7.71/P _s	0.024	1.76	0.221
Grain $\delta^{15}\text{N}$	‰	15.2/Pg	<0.001	0.01	0.919
Straw $\delta^{15}\text{N}$ *	‰	0.05	0.834	4.92	0.057
Grain C	%	1.39	0.286	0.46	0.512
Straw C*	%	7.11/P _s	0.028	0.76	0.409
Grain $\delta^{13}\text{C}$	‰	37.5/P _s Pg	<0.001	7.15/pre	0.020
Straw $\delta^{13}\text{C}$ *	‰	117/P _s	<0.001	40.5/pre	<0.001

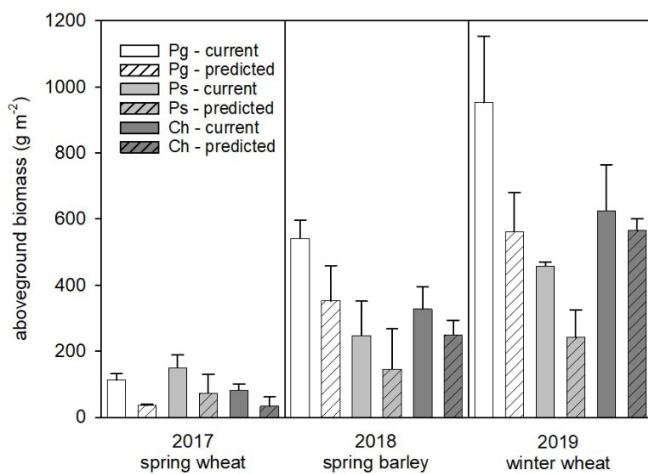
F indicates the mean square of the treatment divided by the mean square of the residuals and *p* is the significance value. The treatment (soil and precipitation) with the higher value is indicated after F. Values with $p \leq 0.05$ are highlighted in bold. *Pg not determined. Pg – gleyic Phaeozem; P_s – sandy Phaeozem; Ch – Chernozem; curr – current precipitation scenario; pre – predicted precipitation scenario

Supplemental Table 5. Two-way ANOVA tables of the impact of soil and precipitation on yield, carbon and nitrogen content, and isotope signature of winter wheat cultivated in 2019

Ergänzungstabelle 5. 2-Wege-ANOVA-Tabelle zum Einfluss von Boden und Niederschlag auf den Kohlenstoff- und Stickstoffgehalt und die Isotopen-signatur von Winterweizen (2019)

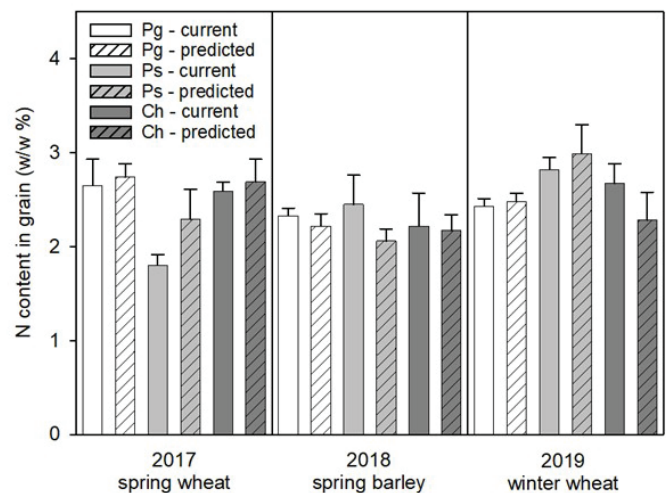
Parameter	Unit	Winter wheat – harvest 03.07.2019			
		Soil		Precipitation	
		F	p	F	p
Grain N	%	0.77	0.488	0.41	0.536
Straw N	%	2.10	0.166	4.92/pre	0.047
Grain $\delta^{15}\text{N}$	‰	36.8/Pg, Ch	<0.001	5.74/curr	0.038
Straw $\delta^{15}\text{N}$	‰	5.22/Pg	0.023	0.17	0.688
Grain C	%	91.6/Pg	<0.001	0.00	0.987
Straw C	%	5.79/P _s , Ch	0.017	0.60	0.452
Grain $\delta^{13}\text{C}$	‰	13.2/P _s	0.002	21.1/pre	0.001
Straw $\delta^{13}\text{C}$	‰	4.05/P _s	0.045	8.38/pre	0.013

F indicates the mean square of the treatment divided by the mean square of the residuals and *p* is the significance value. The treatment (soil and precipitation) with the higher value is indicated after F. Values with *p* ≤ 0.05 are highlighted in bold. Pg – gleyic Phaeozem; P_s – sandy Phaeozem; Ch – Chernozem; curr – current precipitation scenario; pre – predicted precipitation scenario



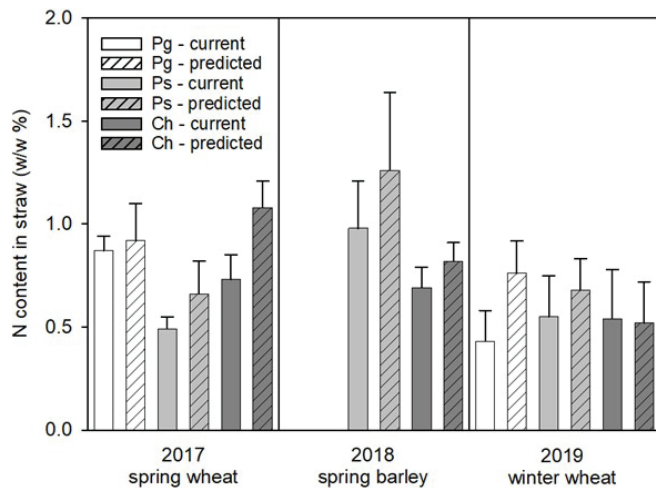
Supplemental Figure 1. Harvests of spring wheat (2017), spring barley (2018), and winter wheat (2019) for the different soil types and precipitation treatments in g m⁻². Given are the arithmetic mean values (*n* = 3) of the above-ground dry biomass, and the error bars represent the standard deviation.

Ergänzungsabbildung 1. Ernten von Sommerweizen (2017), Sommergerste (2018) und Winterweizen (2019) für die verschiedenen Bodentypen und Niederschlagsbehandlungen in g m⁻². Gegeben sind die arithmetischen Mittelwerte (*n*=3). Die Fehlerbalken stellen die Standardabweichung dar.



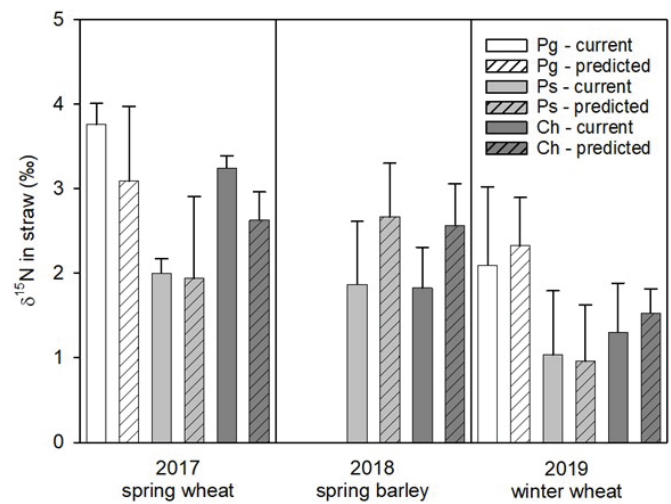
Supplemental Figure 2. Grain N content of spring wheat (2017), spring barley (2018), and winter wheat (2019) for the different soil types and precipitation treatments in ‰. Given are the arithmetic mean values (*n* = 3), and the error bars represent the standard deviation.

Ergänzungsabbildung 2. Stickstoffgehalt im Korn von Sommerweizen (2017), Sommergerste (2018) und Winterweizen (2019) für die verschiedenen Bodentypen und Niederschlagsbehandlungen in ‰. Gegeben sind die arithmetischen Mittelwerte (*n* = 3). Die Fehlerbalken stellen die Standardabweichung dar.



Supplemental Figure 3. Straw N content of spring wheat (2017), spring barley (2018), and winter wheat (2019) for the different soil types and precipitation treatments in ‰. Given are the arithmetic mean values ($n = 3$), and the error bars represent the standard deviation.

Ergänzungsabbildung 3. Stickstoffgehalt des Strohs von Sommerweizen (2017), Sommergerste (2018) und Winterweizen (2019) für die verschiedenen Bodentypen und Niederschlagsbehandlungen in ‰. Gegeben sind die arithmetischen Mittelwerte ($n = 3$). Die Fehlerbalken stellen die Standardabweichung dar.



Supplemental Figure 4. Straw $\delta^{15}\text{N}$ values of spring wheat (2017), spring barley (2018), and winter wheat (2019) for the different soil types and precipitation treatments in ‰. Given are the arithmetic mean values ($n = 3$), and the error bars represent the standard deviation.

Ergänzungsabbildung 4. Delta ^{15}N -Werte des Strohs von Sommerweizen (2017), Sommergerste (2018) und Winterweizen (2019) für die verschiedenen Bodentypen und Niederschlagsbehandlungen in ‰. Gegeben sind die arithmetischen Mittelwerte ($n = 3$). Die Fehlerbalken stellen die Standardabweichung dar.