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Responses of soil water storage and crop water use efficiency to changing climatic conditions: a lysimeter-based space-for-time approach

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Abstract. Future crop production will be affected by climatic changes. In several regions, the projected changes in total rainfall and seasonal rainfall patterns will lead to lower soil water storage (SWS), which in turn affects crop water uptake, crop yield, water use efficiency (WUE), grain quality and groundwater recharge. Effects of climate change on those variables depend on the soil properties and were often estimated based on model simulations. The objective of this study was to investigate the response of key variables in four different soils and for two different climates in Germany with a different aridity index (AI): 1.09 for the wetter (range: 0.82 to 1.29) and 1.57 for the drier (range: 1.19 to 1.77) climate. This is done by using high-precision weighable lysimeters. According to a "space-for-time" (SFT) concept, intact soil monoliths that were moved to sites with contrasting climatic conditions have been monitored from April 2011 until December 2017.

Evapotranspiration (ET) was lower for the same soil under the relatively drier climate, whereas crop yield was significantly higher, without affecting grain quality. Especially "non-productive" water losses (evapotranspiration out of the main growing period) were lower, which led to a more efficient crop water use in the drier climate. A characteristic decrease of the SWS for soils with a finer texture was observed after a longer drought period under a drier climate. The reduced SWS after the drought remained until the end of the observation period which demonstrates carry-over of drought from one growing season to another and the overall long-term effects of single drought events. In the relatively drier climate, water flow at the soil profile bottom showed a small net upward flux over the entire monitoring period as compared to downward fluxes (groundwater recharge) or drainage in the relatively wetter climate and larger recharge rates in the coarser- as compared to finer-textured soils. The large variability of recharge from year to year and the long-lasting effects of drought periods on the SWS imply that long-term monitoring of soil water balance components is necessary to obtain representative estimates. Results confirmed a more efficient crop water use under less-plant-available soil moisture conditions. Long-term effects of changing climatic conditions on the SWS and ecosystem productivity should be considered when trying to develop adaptation strategies in the agricultural sector.

1 Introduction

The amount of water stored within the root zone of the soil and the vadose zone is a central and characteristic component of terrestrial ecosystems. Soil water storage (SWS) is important for provisioning (e.g. crop production, water balance and plant-available nutrients) as well as regulating and supporting ecosystem services (e.g. water, nutrients, climate, flood and drought; Adhikari and Hartemink, 2016; Vereecken et al., 2016). The SWS capacity (SWSC) depends on soil texture, organic-matter content, bulk density and soil structure and is related to the effective field capacity, which can be derived from the soil water retention function (Vereecken et al., 2010). Knowledge of magnitude and temporal variation of the SWS is essential for understanding ecological and hydrological processes and managing ecosystems (Cao et al., 2018). Climate change will modify the temporal availability of soil water, increase the frequency and duration of droughts, affecting the quantity and quality of aquifer recharge, and might affect crop production. Thus future ecosystem productivity (e.g. crop yield) is expected to respond to changes in weather (short-term) and climate (long-term) because it will alter the crop water balance components, such as the SWS, evapotranspiration (ET) and drainage (Yang et al., 2016). How to produce more crop yield with less water is a major challenge in agriculture because (i) water is a limiting factor for crop production in many regions of the world and (ii) predictions of future climate indicate an increasing water limitation for crop production caused by reduced rainfall and changing seasonal rainfall distribution (Lobell and Gourdji, 2012).

Several studies have been conducted to investigate the impact of global climate change on crop water balance components (Sebastiá, 2007; Wu et al., 2015) and crop or grain yield (Ewert et al., 2002; Zhao et al., 2016; Schauberger et al., 2017; Asseng et al., 2019). Understanding the impact of weather signals on agricultural productivity is of crucial importance for managing future crop production, since variations in weather conditions could explain much of the yield variability (Frieler et al., 2017). Temperature rise and changing seasonal rainfall patterns could alter the probability of droughts and affect freshwater resources (Gudmundsson and Seneviratne, 2016; Gudmundsson et al., 2017). Negative impacts of rising temperature on the yield of major crops at the global scale (Asseng et al., 2014; Zhao et al., 2017) are highlighting the potential vulnerability of agricultural productivity to climate change. Schauberger et al. (2017) showed a consistent negative response of US crops under rainfed conditions being mainly related to water stress induced by higher temperatures. In addition to the direct effects of a temperature rise, an elevated atmospheric CO_2 concentration and changes in rainfall amounts on crop yield (Ewert et al., 2002; Asseng et al., 2014; Gammans et al., 2017; Scheelbeek et al., 2018), the higher temperatures could affect crop yields indirectly. Indirect effects caused by increasing the atmospheric water demand, limiting ET due to water stress and reducing the SWS, could in turn lead to a decrease in crop yield (Zhao et al., 2016, 2017). Thus investigating the response of crop water balance components and yield to climate change is important to develop suitable adaptation and mitigation strategies (Albert et al., 2017; Rogers et al., 2017).

Previous studies reported estimates of crop water balance components and crop yield mostly based on either manipulative experiments or observational studies to predict the ecological response of crops to climate change (Yuan et al., 2017). Wu et al. (2015) showed that the inter-annual variation of the SWS at northern middle and high latitudes increased under a warmer climate with higher values during the wetter and lower values of the SWS during the drier season. In this case, the frequency of water logging events or soil crack formation will increase and probably alter soil properties such as macroporosity and the SWSC and thus affect vadose zone hydrology at different scales (Robinson et al., 2016; Hirmas et al., 2018). Robinson et al. (2016) showed for a manipulative long-term experiment that intense summer droughts altered the soil water retention characteristic and lowered the SWSC.

Nevertheless, current knowledge of changes of the SWS are still limited mostly to the analysis of soil moisture observations related to restricted soil volumes and soil moisture ranges (Mei et al., 2019; Yost et al., 2019). As an alternative method, weighable lysimeters allow for the direct observation of the SWS by monitoring the temporal changes of the total soil mass in mostly cylindrical containers. However, the use of weighable lysimeters was often limited in the past to the quantitative determination of the water balance components of precipitation (P), evapotranspiration and subsurface inflow (Q_{in}) and outflow (Q_{out}; e.g. drainage); the change of the SWS was obtained as residual of the water balance components (e.g. Herbrich et al., 2017; Groh et al., 2018b). This approach accumulated all possible errors introduced by other components into the SWS, causing a relatively low precision. The direct derivation of the SWS from lysimeter mass changes could provide a new perspective on the use of lysimeter data as an additional model calibration variable and for lysimeters that are large enough to fully capture the complete soil profile with the relevant soil horizons and intact soil structures to be representative for the pedon scale.

The water use efficiency (WUE) links the carbon and water exchange between vegetated soil and the atmosphere (Niu et al., 2011). Several definitions have been used to describe the WUE at the leaf or ecosystem level (for more details see Zhou et al., 2017). At the ecosystem level, the WUE, defined as the ratio between grain yield or total biomass and the water lost to the atmosphere by ET (Fan et al., 2018), is one possible way to quantify the impact of changes in environmental conditions and of management decisions (e.g. irrigation) on agricultural productivity. The use of ET instead of transpiration (T) only for calculating the WUE represents water use efficiency at the ecosystem rather than leaf level because it accounts for evaporation (E), which is also dependent on crop-specific development and soil management. The WUE provides insights in to better managing and understanding the productivity and ecological functioning of agricultural ecosystems (Zhang et al., 2015). The prevailing general hypothesis for the WUE is that plant productivity increases with increasing water use (ET; Hatfield and Dold, 2019), which implies that WUE efficiency is a linear function of the water used by a crop to produce grain yield or the total aboveground biomass. But several studies have shown that crop WUE was negatively correlated with annual rainfall and that plants achieved their maximum crop WUE under less-favourable soil water availability (Zhang et al., 2010; Ponce-Campos et al., 2013; Xiao et al., 2013; Zhang et al., 2015). The last statement might imply that plants are able to adapt their water use during drought conditions by improving their WUE or that there are simply fewer non-productive water losses by evaporation. Nevertheless, temperature above a certain threshold (extremely high temperature) especially during the reproductive period (Gourdji et al., 2013) or due to drought and heat stress reduce yield. However, such investigations are often focused on one specific environmental variable (e.g. P or temperature) in manipulation experiments. This basically ignores joint effects of several climate variables on the crop WUE in climate impact research studies. The impact of altered climatic conditions on different agricultural ecosystems within manipulative experiments has not been thoroughly studied yet, due to problems to either realistically manipulate the climatic conditions at a specific site or to move an intact soil to another site with contrasting climatic conditions.

Here, we hypothesize that the WUE will not increase for drier climate because a change in plant productivity will simultaneously alter the water use (ET) and thus describe the WUE as a linear function between both variables. In addition we wanted to test if observed lysimeter mass changes can be used to monitor the long-term change of the SWS, which might be in addition to water flux observation a useful dataset for the calibration of vadose-zone models. We used observations from a German soil–climate crossed factorial experiment (TERrestrial ENvironmental Observatories; TERENO-SOILCan; Pütz et al., 2016). The lysimeter network of TERENO-SOILCan has been initiated to assess effects of climatic changes on arable and grassland soil ecosystems including the water balance components (ET, SWS and net drainage) and crop characteristics including yield, yield quality and the WUE. As part of this project, arable-land lysimeters filled with four different soils were transferred within and between TERENO observatories (space-for-time – SFT; see details in Pütz et al., 2016) to expose soils from originals sites to other climatic conditions. The space-for-time approach means that soils are translocated in space instead of waiting at the same location for changes in climatic conditions in time. The concept was initially intended to evaluate the impact of climate on agricultural ecosystems (Pütz et al., 2016). It represents basically a crossed soil type and climate experimental setup that could allow for quantifying changes in the soil water balance and the crop production as a response to imposed variations in climatic conditions. Results from this experimental setup can primarily be used to evaluate models that predict changes in response to possible future climatic conditions.

Our objectives were (i) to develop an approach to obtain time series of changes in the SWS directly from lysimeter data, (ii) to determine the other soil water balance components (P, ET, inflow and drainage) of soils each exposed to two different climates, (iii) to compare the dynamics of net flux (inflow and drainage) and the SWS for the same soils in relatively dry and wet climates, and (iv) to test the hypothesis that the WUE of crops remains constant under changing climatic conditions in these crossed soil type and climate experiments. The analysis was based on lysimeter data from April 2011 until December 2017.

2 Material and methods

2.1 Site descriptions

The study was conducted at the experimental field sites Selhausen (50°52′7″ N, 6°26′58″ E; Se) and Bad Lauchstädt (51°23′37″ N, 11°52′41″ E; BL), which are part of the Eifel/Lower Rhine Valley and the Harz/Central German Lowland Observatory of TERENO in Germany (Wollschläger et al., 2016; Bogena et al., 2018), respectively. The TERENO-SOILCan lysimeter network was established at several experimental stations across a rainfall and temperature gradient. Local excavated lysimeters (i.e. intact soil monoliths) were transferred between the stations to subject them to different climate regimes so as to generate a crossed soil–climate setup according to the space-for-time substitution approach. It should be noted that we did not follow the SFT substitution as used in ecological (e.g. Pickett, 1989; Blois et al., 2013; Wogan and Wang, 2018) or hydrological (e.g. Scanlon et al., 2005; Troch et al., 2013) studies. Typically such SFT studies assume that spatial and temporal variations are equivalent (Pickett, 1989). By translocating soils from one test site to another while keeping some of the lysimeters at their original site, we actually account for unsuspected effects from the past. In this way we eliminate effects caused by past local events such as disturbances, pedogenesis or site management. This is in contrast to the standard SFT approach. The spatial transfer of intact soil monoliths in the lysimeters followed an assumed direction of climatic changes of increased temperature and precipitation. For this study, we considered all arable-land lysimeters at the central sites Bad Lauchstädt and Selhausen of the TERENO-SOILCan lysimeter network. Each central experimental site contains three replicates of soils from different locations: Bad Lauchstädt (Haplic Chernozems; loess), Dedelow (Dd;

Calcic Luvisols and Haplic Luvisols; glacial till), Sauerbach (Sb; Colluvic Regosols; colluvial deposits) and Selhausen (Haplic Luvisols, loess). This allows for the investigation of the response of the corresponding soil type under different climates. The transfer of soils between the research stations imitates a change in climatic conditions and compares for identical soils the effects of different climatic conditions on crop yield and soil water fluxes with those at the original location. By transferring lysimeters between stations, the "climatic shift" is abrupt such that we are not able to follow the gradual changes of the soil ecosystem over time as suggested in standard SFT approaches. Instead, crop yield and fluxes for the same soil under different climatic conditions are compared. Further information on soil texture and the transfer of soil monoliths from the TERENO observatories to the central sites can be taken from Tables S1 to S2 (see Supplement). The transferred eroded Luvisol soil monoliths from Dedelow have a varying soil depth to the clay illuviation horizon (B_t) and to the marly, illitic glacial till (C horizon). They represent part of the erosion gradient typically observed in agricultural landscapes of hummocky ground moraines (Sommer et al., 2008; Rieckh et al., 2012; Herbrich et al., 2017). Detailed information about the lysimeter design and general experimental setup of TERENO-SOILCan can be found in Pütz et al. (2016). The climatic conditions of the central sites from 1 January 2012 to 31 December 2017 (complete years) are shown in Fig. 1 according to Walter and Lieth (1967). Although the patterns in average monthly temperature values are relatively similar at both sites (Fig. 1), a more pronounced amplitude of the temperature variations over the year could be found in Bad Lauchstädt (representing a more continental climate) as compared to the more temperate and humid climate (sub-oceanic or sub-Atlantic) in Selhausen (Fig. 1). The average annual grass reference evapotranspiration (ET_0) calculated with the FAO-56 (Food and Agriculture Organization of the United Nations) Penman–Monteith method (Allen et al., 2006) is slightly higher at Bad Lauchstädt (710 mm) than at Selhausen (694 mm). Larger differences are shown in the annual rainfall and the rainfall distribution over the year (Fig. 1). The lower annual P in Bad Lauchstädt (458 mm) than in Selhausen (644 mm) corresponds to a higher aridity index ($AI = ET_0 P^{-1}$; see data repository) of 1.57 for Bad Lauchstädt than for Selhausen (1.09). The rainfall distribution over the year was more uniform in Selhausen, whereas the probability of relatively dry periods in spring (April) and late summer (September) was higher in Bad Lauchstädt. Thus, the climatic conditions at the SOILCan experimental sites can be defined as drier for Bad Lauchstädt and wetter at Selhausen, which corresponds well to long-term weather station data, from stations at (Nord; German weather service) and at Forschungszentrum Jülich (see Fig. 1c and d).

2.2 Soil water storage

Monthly changes in the SWS (ΔSWS) were calculated from lysimeter observations as

$$\Delta \mathrm{SWS} = \Delta W + \Delta L_{\mathrm{yscor}}, \tag{1}$$

where ΔW is the monthly lysimeter mass change and $\Delta L_{\mathrm{yscor}}$ corresponds to mass changes by maintenance, harvesting, or other disturbances that occur accidently (e.g. erroneous load cells) or naturally (e.g. animals). The variable ΔW was directly obtained by analysing lysimeter mass data (average value: 00:00 to 02:00). defined as

$$\Delta W = W_{i+1} - W_i, \tag{2}$$

where W is the lysimeter mass at the beginning of month i. The variable $\Delta L_{\mathrm{yscor}}$ was determined from monthly changes of lysimeter mass during maintenance work. Less than 0.6 % of ΔSWS values could not be calculated, because lysimeter mass data at the beginning of the corresponding month were missing. A linear regression model obtained for the entire time series between ΔSWS of the soils was used for interpolation to fill the gaps. This was first based on ΔSWS from surrounding lysimeters of the same soil type, and if these were not available, then the average values of ΔSWS obtained from all available lysimeters at the respective station were used.

2.3 Crop water use efficiency, grain yield and yield quality

In total 12 arable-land lysimeters (three replicates of four soil types) with a surface area of 1 m^2 and a depth of 1.5 m were embedded within larger fields at the respective central experimental site at Selhausen (250 m^2) and Bad Lauchstädt (720 m^2). The same crops were grown, and identical tillage and crop management procedures were carried out at both sites and in the field around the lysimeters. The lysimeters were cultivated with peas (*Pisum sativum* L.; cultivar: Mascara), winter barley (*Hordeum vulgare* L.; cultivar: Lomerit), winter canola (*Brassica napus* L.; cultivar: Adriana), oat (*Avena sativa* L.; cultivar: Max G), winter wheat (*Triticum aestivum* L.; cultivar: Glaucus), winter barley (*Hordeum vulgare* L.; cultivar: Antonella) and winter rye (*Secale cereal* L.; cultivar: SU Santini), whereas the applications of seasonal plant protection, crop growth regulators and nitrogen fertilizer (see Table S3) have been adapted to the conditions of local farmers at the respective experimental site. Dry mass of the yield and plant residual matter were gravimetrically determined with a precision balance (Selhausen: EMS 6K0.1, KERN, Balingen-Frommern, Germany; Bad Lauchstädt: LC 6200 D, Sartorius, Göttingen, Germany) after drying at 75 °C for 24 h (Bad Lauchstädt) and at 60 °C for > 24 h (Selhausen; until reaching a constant weight). The determination of the total nitrogen of the dry yield and plant residual material was

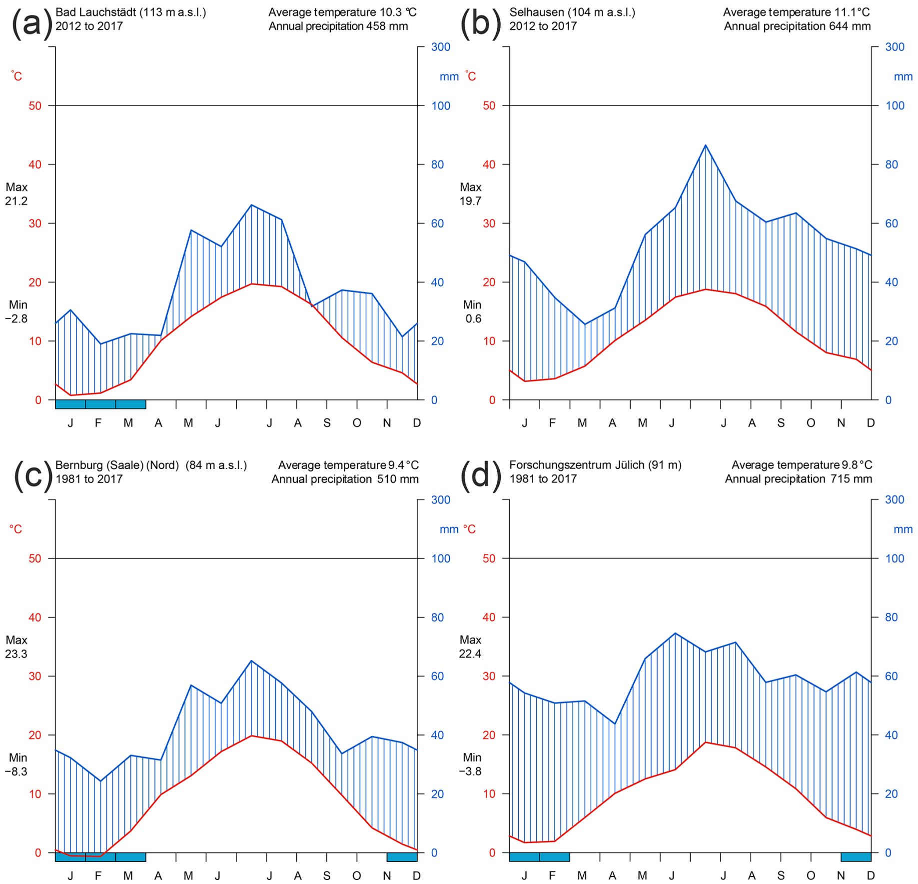

Figure 1. Climate diagrams according to Walter and Lieth (1967) for Bad Lauchstädt **(a)** and Selhausen **(b)** for 2012 to 2017 and Bernburg (Saale) (Nord) **(c)** and Forschungszentrum Jülich **(d)** for 1981 to 2017. Data were obtained from the SOILCan weather stations at Selhausen and a climate station at Bad Lauchstädt above sea level. The long-term weather data were taken from the weather stations of the Deutscher Wetterdienst (Germany's national meteorological service) at Bernburg (Saale) (Nord) and the Forschungszentrum Jülich. The blue bars at the bottom of subplot **(a, c, d)**) indicate months where frost is likely to occur.

obtained with an elementary analyser (vario EL cube, elementar, Langenselbold, Germany).

Equation (3) was used to calculate the crop WUE ($kg\,m^{-3}$).

$$\mathrm{WUE} = \frac{Y}{\mathrm{ET}}, \tag{3}$$

where Y is the grain yield ($kg\,m^{-2}$) and ET ($m^3\,m^{-2}$) is the measure of the consumed water during the growing season of the corresponding crop (Katerji et al., 2008). The growing periods of the crops were defined as the time between sowing and harvest (see Table S3). The required ET during the growing season was estimated based on the monthly water balance equation and observed precipitation in millimetres per month as

$$\mathrm{ET} = P - \Delta\mathrm{SWS} - Q_{\mathrm{net}} - \Delta L_{\mathrm{ysvol}}, \tag{4}$$

where Q_{net} is the monthly sum of net water flux across the lysimeter bottom ($Q_{\mathrm{net}} > 0$: drainage; $Q_{\mathrm{net}} < 0$: capillary rise) and $\Delta L_{\mathrm{ysvol}}$ is mass change determined from monthly soil water sampling volume. P was measured with a tipping bucket rain gauge (15189, LAMBRECHT meteo, Göttingen, Germany) at Bad Lauchstädt (experimental station Bad Lauchstädt) and with a weighing rain gauge (Ott Pluvio2 L, Ott, Kempten, Germany) at Selhausen (Se_BDK_ 002). Data of the latter station are available at the TERENO data portal (Kunkel et al., 2013). The Ott rain gauge was installed in April 2013; data before April 2013 were estimated by linear regression models and P data from surrounding climate stations of the TERENO data portal (station names: SE_BDK_002; RU_BCK_003; RU_K_001; ME_BCK_001), which can be used to interpolate between the given data points. We used the R software (R-Core-Team, 2016) and the function lm of the package stats (R-Core-Team, 2016) to set up linear regressions. The coefficient of determination (R^2) was used to determine the goodness of fit of the linear regression. A stepwise gap-filling approach was used to gap-fill missing P data after April 2013, which consisted of an analysis of data from other meteorological stations that were operating and missing values were filled based on the observation which had the highest R^2. Monthly Q_{net} values were obtained from mass changes of the leachate from the lysimeters, collected with a weighable reservoir tank. The lysimeter bottom-boundary pressure head condition was imposed by a pumping mechanism, which enabled either outflow or inflow according to differences in pressure head values at 1.4 m depth between the lysimeter and surrounding field soil. This control of the bottom boundary allowed for imitating the upward and downward water fluxes and representing ET processes in lysimeters (Groh et al., 2016) more realistically and comparable to the intact soil profile. More technical details can be found in Pütz et al. (2016). Missing data in the time series of Q_{net} were filled for small gaps of about 1 min by linear interpolation and for gaps between > 1 and 10 min by using a moving average with a window width of 30 min. Larger gaps in the time series were filled by average water flux values from other lysimeters of the same soil type. Nearly 5 % of monthly ET values were found not plausible perhaps due to water loss by leaking during periods with water-saturated conditions at the lysimeter bottom. These conditions occurred mainly in winter, when monthly ET fluxes were in general relatively low as compared to summer conditions so that potential error was low and easily detectable. A linear regression based on either single or average ET values from other non-affected lysimeters with similar soils were used for interpolation to fill the gaps. Detailed information on the monthly water balance data and missing data can be taken from the TERENO data portal (see section Data availability).

3 Results and discussion

3.1 Soil water storage change

For the observation period (April 2011–January 2018), evapotranspiration and cumulative soil water storage change (ΔSWS) differed at both stations, Selhausen and Bad Lauchstädt, in the amount and temporal development between transferred soils and those from the original site (Fig. 2). The variability in terms of the standard deviation of ΔSWS and ET of the three replicate soils was small and ranged across the different soils for ΔSWS between 4.3 and 7.4 mm and for ET between 3.7 and 5.5 mm. This clearly demonstrates that the differences in ΔSWS and ET between the same soils at original and new locations are larger than their scatter (Fig. 2). This suggests that uncertainty in the calculation of water fluxes were in general smaller than effects of transferring soils between the test sites. Larger deviations in ΔSWS between origin and transferred soils were visible for the crop winter canola after the date of harvest in summer 2013 (soils from BL, Sb and Se; Fig. 2b, d, h) and winter barley for 2016 (all soils). The largest depletions of the SWS during the entire observation period could be observed for all soils during the spring–summer period (March and July) in 2015. At Bad Lauchstädt, the aridity index ($\text{AI} = \text{ET}_0 P^{-1}$) of 2.7 for March–July 2015 was larger as compared to the average AI value of 2.0 calculated for all March and July periods between 2012 and 2017. Also the value of the AI for Selhausen was with 2.0 slightly larger as compared to the average AI value of 1.6 for all March–July periods. The SWS depletion in 2015 was larger at both sites for soils from Bad Lauchstädt (Fig. 2b) and Sauerbach (Fig. 2d) as compared to that of the other two soils from Dedelow (Fig. 2f) and Selhausen (Fig. 2h). The Sb and BL soils were strongly desiccated by the winter wheat crop in 2015, which can be seen from ET June 2015 for BL and Sb of about 125–175 mm month^{-1} (Fig. 2a and c) was larger than for Dd and Se soils of about 100–125 mm month^{-1} (Fig. 2e and g) even for the soils exposed to the drier climate in Bad Lauchstädt. For the BL (Fig. 2b) and Sb (Fig. 2d) soils, the amount of rainfall after the growing season of 327 mm (August 2015–April 2016) in Bad Lauchstädt was not sufficient to compensate for ET and drainage such that the soil profile did not return to a SWS capacity (i.e. typical spring moisture) at the end of the winter period characterized by a value close to 0 of the cumulative ΔSWS. The soil moisture deficit from 2015 was carried over to the growing seasons of 2016 and even of 2017. For the Dd and Se soils (Fig. 2f and h), the SWS deficit during the 2015 growing season under the climate of Bad Lauchstädt was less and the amount of precipitation after the growing season was sufficient for the soils to return to a typical SWS value, although this value was reached later and not before the next spring. The AI of 1.77 at BL in 2015 (January–December) was considerably higher than the average AI for the 5-year period at BL (1.57). For the same year 2015, the AI was 1.13 at Se and thus only slightly higher than the 5-year average AI value of 1.09. For all soils in Se (blue lines in Fig. 2b, d, f and h), the amount of precipitation after the growing season of 501 mm for 2015 (August 2015–April 2016) was sufficient for the lysimeters to return to their “typical” SWS value at the end of the winter. These results indicate soil-type-dependent changes in the SWS during drought periods. The annual carry-over of soil moisture deficits demonstrates the vulnerability towards drought risks even for finer-textured soils, despite having an overall larger SWSC than coarser-textured soils. This might be related to a higher infiltration capacity of the coarser-textured soil, which allows for a more-rapid recharge. The infiltration capacity is dependent on the conductivity at the soil surface. Silting and cracking, which more often occur at the soil surface of fine-textured soils, affects the macropore structure (destruction of soil aggregates) and changes the infiltration. However, no surface runoff was observed during the observation period, and qualitative observations on cracking were made during the harvest time, but the soil surface has been modified by tillage, and the topsoil organic-matter content and the plant roots are counteracting silting and cracking. This suggests that the annual carry-over of soil moisture deficits was not related to a different infiltration capacity of the soil. The observed stronger depletion of soil water corresponds with soil drying reports from larger-scale observations on the occurrence of a severe drought during the summer of 2015, where effects of the drought have been observed from a climatological (Ionita et al., 2017) and hydrological (Laaha et al., 2017) perspective. The carry-over of soil moisture deficits to the time after the drought at the local scale in Bad Lauchstädt agrees well with the results from Laaha et al. (2017), which showed for several stations in Europe that soil water storage (catchment scale) at the end of the study period (November 2015) has not totally recovered from the summer drought in 2015.

Furthermore, changing climatic conditions and a more frequent occurrence of drought could alter the SWSC because of the increasingly unavailable pore spaces due to different sources, including physical processes, e.g. swelling and shrinking (te Brake et al., 2013; Herbrich and Gerke, 2017), biological processes, e.g. vegetation-induced soil desiccation that enhanced soil cracking (Robinson et al., 2016), and biochemical processes, e.g. enhanced organic-matter mineralization, due to increasing oxidation of the organic horizons during dry periods (Robinson et al., 2016), which will consequently result in a degradation of organic soil structure or change in the soil wettability (Ellerbrock et al., 2005).

3.2 Net drainage

The water fluxes across the suction rake system at the lysimeter bottom in 1.5 m depth were cumulated to monthly net drainage fluxes (Q_{Mnet}). The time series of Q_{Mnet} for all soils at Se, the site with a relatively wet climate, were in general directed downward during the winter months and upward (capillary rise) during spring and summer (Fig. 3). However, the magnitude of monthly fluxes Q_{Mnet} differed between the soil types (e.g. soils in Se for 2012 or 2013; see Fig. 3); Q_{Mnet} for lysimeters with the coarser-textured soils from Dd (Fig. 3c) was mostly larger (e.g. drainage during bare fallow 2014) than for that with the finer-textured soils from BL (Fig. 3a), Sb (Fig. 3b) and Se (Fig. 3d). For the same soils under the relatively dry climate in BL, time series of Q_{Mnet} were rather similar, with the largest values of upward fluxes for the soil from Dd (Fig. 3c). The magnitude of Q_{Mnet} for soils under the BL climate was mostly smaller for drainage and larger for upward-directed fluxes as compared to the Q_{Mnet} values for the soils under the wet climate in Selhausen.

The Q_{Mnet} time series (Fig. 3) demonstrate that weather conditions in 2015 impacted the soil water fluxes in the following years: under the dry climate in BL, hardly any drainage was observed for all soils after 2015. This indicates that the soils remained so dry during the winter period that downward water percolation or groundwater drainage was limited. The lack of water recharge during winter also affected the upward-directed Q_{Mnet} flux rates in the following years, which generally decreased after 2015, especially for soils from BL and Sb. The nearly unchanged Q_{Mnet} values for the soils at BL after 2015 indicate that soil water saturation and dynamics is limited throughout the soil profile.

The annual net water fluxes (Q_{Anet}) at the bottom (in 1.5 m) of the same soils under the dry and wet climates are compared in the form of scatterplots (Fig. 4). The scatterplots clearly show that fluxes were in general directed upward (i.e. negative values of Q_{Anet} for soils under a dry climate in BL; positive values of Q_{Anet}, i.e. drainage) were only observed for 2011 and 2014 (Fig. 4). The larger values of Q_{Anet} for 2014 could be due to the lower ET after an earlier harvesting of the oat crop and a longer bare soil period without crop transpiration. The coarser-textured soils from Dedelow showed the largest range of Q_{Anet} values (from -78 to $+164$ mm) at the site with a relatively dry climate (BL) during the observation period of 2011–2017. This range could be explained by variation in soil water storage capacities between Dd soils, which depended on the thickness of the upper soil horizons that were modified by soil erosion (Herbrich et al., 2017). The long-term average values of Q_{Anet} for all soils in the dry climate were negative and varied only in a small range (from -18 to -28 mm; see Supplement Table S2). Long-term negative groundwater recharge is only possible at sites where groundwater can be replenished, for instance, by lateral subsurface water flow. Whether the Q_{Anet} flux under the BL climate will continue to be negative for all soils would require a longer time series. Nevertheless, a low and even negative groundwater recharge has not only an impact on the groundwater quantity, but it will also affect the groundwater quality. In the case of a small net recharge, the concentrations of solutes from agricultural fertilizers, pesticides, and those of dissolved minerals and salts in the water-filled soil pores will become relatively high, and soil water movement still remains negligibly small. Thus under conditions of relatively small leaching rates, solutes including plant nutrients will largely be retained within the soil's root zone. Soils and soil horizons may accumulate carbonates under long-term conditions of net negative leaching (e.g. BL soil with Haplic Chernozems) or if leaching is small such that the carbonates from the topsoil horizons precipitate already in the subsoil within the 1.5 m soil monoliths like in the Ccv (C – parent material horizon; c – secondary carbonates; v – weathered) horizons in Dd subsoil of Calcic Luvisols (see soil profile descriptions in Herbrich and Gerke, 2017) and eventually salt.

Q_{Anet} values under a relatively wet climate (in Se) were for all soils positive, indicating in general downward-directed drainage fluxes (Fig. 4). The long-term average Q_{Anet} values ranged between 49 to 119 mm (see Table S2), depending on the soil type. The Q_{Anet} value was larger for the coarser-textured soil from Dd (Fig. 4c) as compared to the other soils. For 2013 (winter canola crop), the Q_{Anet} fluxes were negative for all finer-textured soils (i.e. Bad Lauchstädt, Sauerbach and Selhausen; Fig. 4a, b, d), which might be related to the deeper-reaching root system of the crop canola (Breuer et al., 2003) and a consequently larger plant water uptake in com-

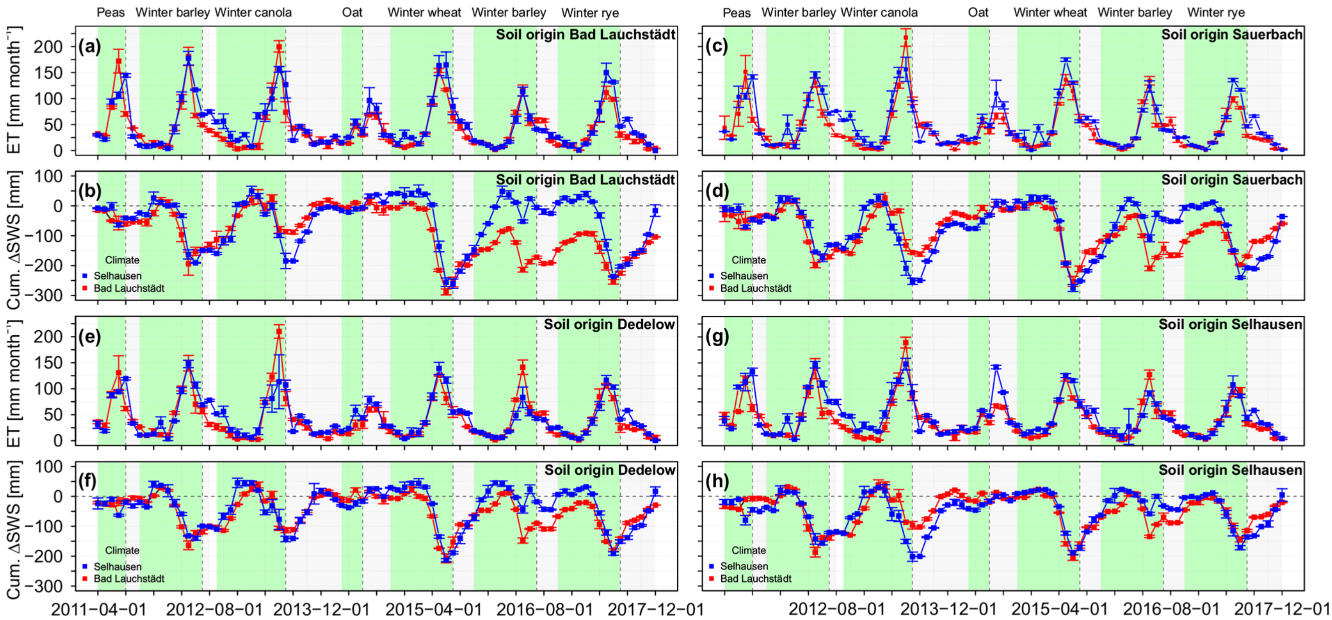

Figure 2. Monthly evapotranspiration (ET) and cumulative monthly changes in soil water storage (ΔSWS) from April 2011 until January 2018 at the lysimeter stations in Selhausen and in Bad Lauchstädt for soils from Bad Lauchstädt **(a, b)**, Sauerbach **(c, d)**, Dedelow **(e, f)** and Selhausen **(g, h)**; mean values (dots) and standard deviations (error bars) are from three individual lysimeter monoliths of each soil. The background colour corresponds with the cropping periods at the TERENO-SOILCan lysimeters: bare soil (white) and crops (green). Dates are given in the figure in the YYYY-MM-DD format.

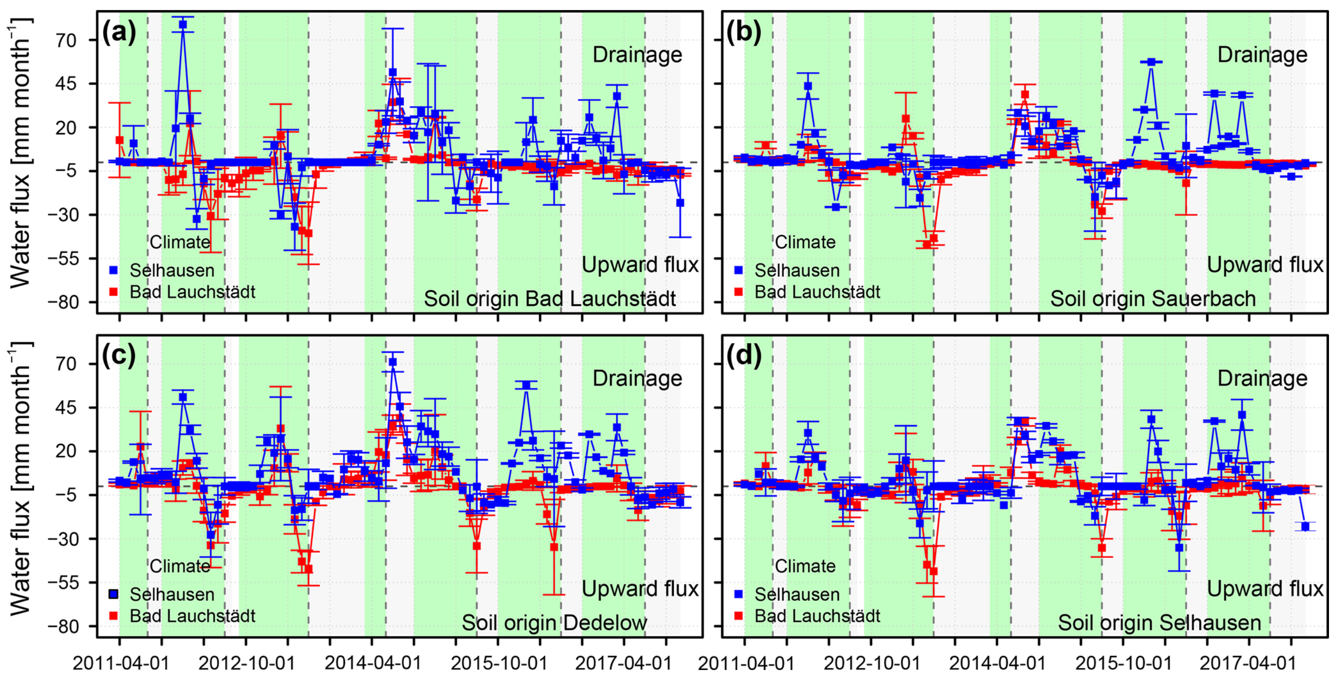

Figure 3. Monthly net water fluxes across the lysimeter bottom in 1.5 m soil depth from April 2011 until January 2018 at the stations Selhausen and Bad Lauchstädt for soils from **(a)** Bad Lauchstädt, **(b)** Sauerbach, **(c)** Dedelow and **(d)** Selhausen; mean values (dots) and standard deviations (error bars) are shown. Positive values are defined as drainage, and negative values are defined as upward-directed water flux from capillary rise. Error bars indicate the variability of storage changes between individual lysimeters of each soil group. The background colour corresponds to different crops lysimeter cover types: bare soil (white) and different crops (green). Dates are given in the figure in the YYYY-MM-DD format.

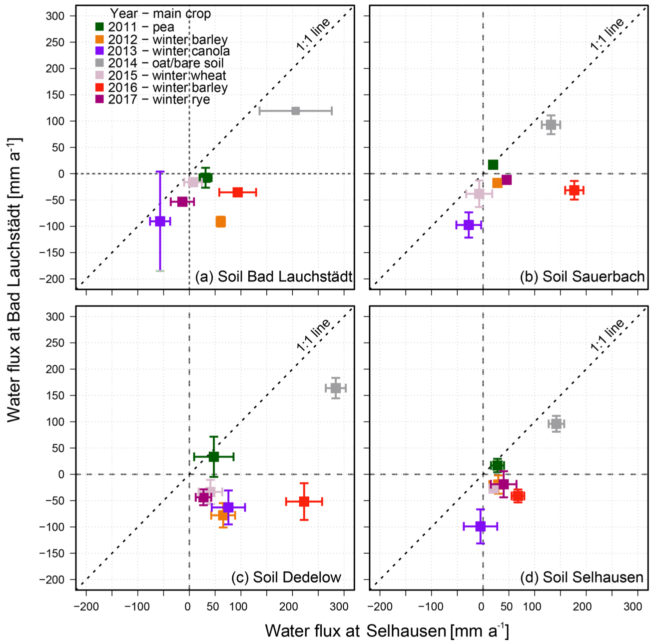

Figure 4. Comparison of net fluxes for the same soils at two sites: annual observed net soil water flux at 1.5 m soil depth of soils from **(a)** Bad Lauchstädt, **(b)** Sauerbach, **(c)** Dedelow and **(d)** Selhausen under a dry climate (Bad Lauchstädt) and wet climate (Selhausen) for the years between 2011 and 2017; average values (symbols) and standard deviations (error bars) for observations are from the same soil.

parison to other crops. Upward-directed Q_{Anet} values were observed during the year 2017 for the soils from Bad Lauchstädt under the winter rye crop (Fig. 4a) and during 2015 for the soils from Sauerbach under winter wheat (Fig. 4b).

3.3 Crop yield and water use efficiency

The grain yields were in general larger for a dry climate at Bad Lauchstädt than for a wet climate at Selhausen, except for the peas (Fig. 5a). The pea crop had in comparison to the other cereal crops a relatively short vegetation period and depends more on conditions during germination in early spring than on differences in climatic conditions in late spring and summer. For the other crops the spread of fungal pathogens under a more humid climate (Talley et al., 2002; Agam and Berliner, 2006) and frequent occurrence of dew formation (Xiao et al., 2009; Groh et al., 2018a; Brunke et al., 2019; Groh et al., 2019) could explain the generally lower yield of grain crops for soils under a wet climate in Selhausen. However, appropriate crop management with one to three applications of fungicides during the growing season (see Table S3), except for pea crop in 2011 (BL and Se) and winter rye in 2017 (Se), should have prevented the spread of fungal diseases and their impact on crop yield such that other reasons have to be considered. The yield varied for most crops among the soil replicates at a certain site, which can be described by the coefficient of variation (CV), for values of which below 28 %, except for peas, which showed for all soils a high value, for winter canola grown on finer-textured soils in Se (BL, Se see Table S4) and for winter barley (Dd and Sb in 2012, Sb in 2016) cropped at Se. For winter canola this might be related to a higher loss of rapeseed during manual harvesting, natural pod shattering, cleaning and threshing (Alizadeh et al., 2007; Kuai et al., 2015). The CV value of the observed yield variability between each soil type corresponds to values reported between 5 % and 27 % by Joernsgaard and Halmoe (2003) and Wallor et al. (2018). The yield of winter wheat (7.8 t ha^{-1}; see Table S4) for the soil from BL at BL agreed well with observations on yields from a long-term fertilization experiment at the BL site (Merbach and Schulz, 2013), which demonstrates the high yield potential of the soil from BL.

The scatterplot of the total biomass (Fig. 5b) shows that most crops produced relatively similar amounts of total aboveground biomass at both sites, with the exception of winter barley in the years 2012 and 2016. The crops could probably use comparable amounts of solar radiation during the observation period (average annual radiation from 2011 to 2017, obtained from the weather stations; BL: 1181.4 kWh m^{-2} and Se: 1180 kWh m^{-2}). Despite a similar amount of radiation received by the crops, the harvest index, which is defined as the ratio of yield to the total biomass, was found to be larger under a dry climate than under a wet climate (Fig. 5c). This means that crops under a dry climate were more productive with respect to crop yield than under a wet climate. The crop ET (i.e. ET related to the vegetation period) was larger under the wet than under the dry climate (Fig. 5d), and the corresponding crop water use efficiency was larger at the site with the relatively dry (BL) as compared to the wet (Se) climate (Fig. 5e). These results demonstrated that plants were more efficient to produce yield at a site with a suboptimal water supply. The present results are in line with earlier findings from Zhang et al. (2015), who showed that the WUE reached a maximum under warm and dry and a stable minimum under warm wet climatic conditions. Also when the WUE was calculated based on the total aboveground biomass, a higher WUE was observed for the corresponding crop under a dry than under a wet climate (Fig. 5f), which demonstrated that climatic conditions were not only beneficial for the grain yield but also for that of the straw. However, differences in fertilizer application (see Table S3) with a lower nitrate application in the wet site could be another reason for the differences in yield and biomass production.

The lower WUE under a wet climate might be related to higher soil evaporation and plant canopy interception evaporation. Kunrath et al. (2018) found for the crop tall fescue that limiting nitrogen supply conditions negatively affected WUE values by a reduced leaf area index, leaf photosynthesis and radiation efficiency, which hence increased the ratio of soil evaporation to transpiration. Thus, we further compared the

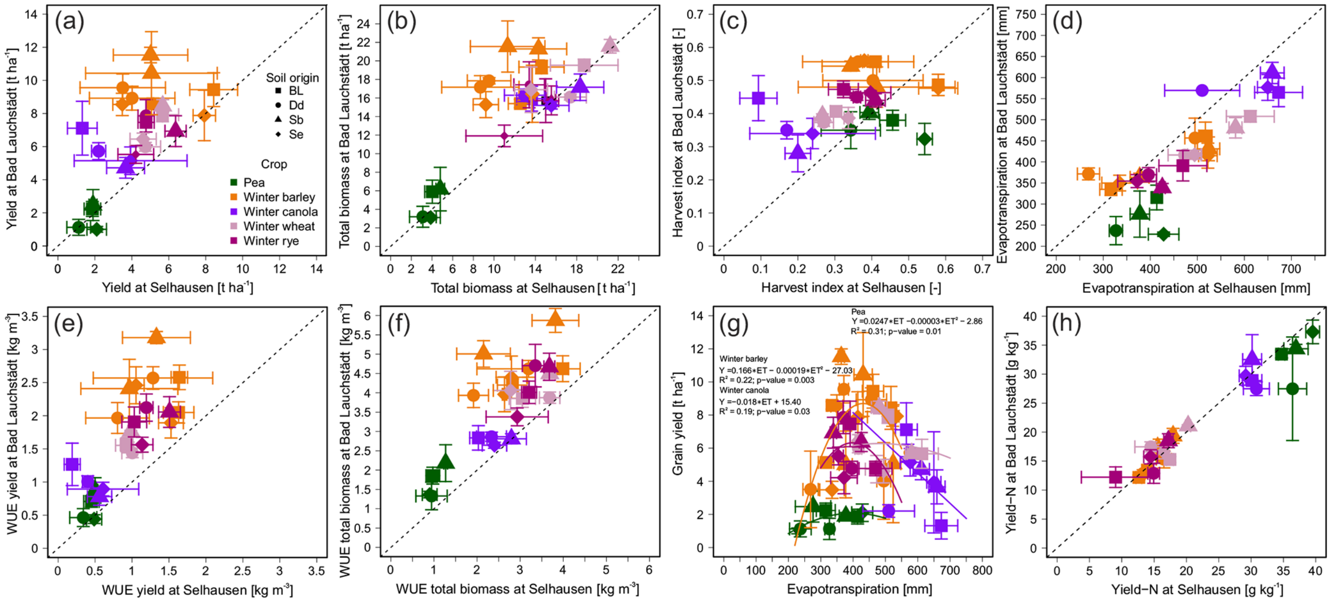

Figure 5. Comparison of parameters related to annual crop yield and ET for the same soils from Bad Lauchstädt, Dedelow, Sauerbach and Selhausen (three lysimeters each origin) at the two sites with a relatively dry (Bad Lauchstädt) and wet climate (Selhausen); average values (symbols) and standard deviations (error bars) between observations are from the same soils for **(a)** observed yield, **(b)** total biomass, **(c)** harvest index, **(d)** evapotranspiration, **(e)** water use efficiency (WUE) from yield, **(f)** the WUE from total biomass and **(h)** nitrogen (N) content in the grain yield as well as **(g)** the relationship between grain yield and evapotranspiration of all soils and crops during the years 2011–2017.

ET during periods when ET was either transpiration (ET_T) or evaporation (ET_E) dominated. The transpiration-dominated period was defined from the beginning of April, which corresponds well with the temporal increase of the monthly ET, until the time when plants reached the growth stage of ripening/maturity of their fruit or seeds about a month before harvest (see Table S3). The rest of the vegetation period was defined as the evaporation-dominated period. Evaporation was considered to be non-productive water use. The cumulative values of ET, ET_T and ET_E during the observation period are shown in Table 1. The differences for ET_E between all soils in the dry and wet climate from 359 to 576 mm was larger than the differences for ET_T (range: −72 to 199 mm). Especially the higher rate of soil evaporation (ET_E) at Selhausen contributed to the lower WUE under wet climate.

The relationship between yield and ET was reported to correspond with the productivity function of crops (grain yield vs. ET) and often assumed to be linear (Tolk and Howell, 2009; Wichelns, 2014). However, for our present data, a quadratic productivity function (Fan et al., 2018) of the winter barley and pea crops (Fig. 5g) rather than a linear one could explain the observed larger WUE of soils under a dry climate at Bad Lauchstädt. The crop winter canola could be best described by a linear productivity function with a negative slope (Fig. 5g). The other crops, winter rye and winter wheat, could be described by neither a linear nor a quadratic function. Longer time series with more crop yield observations under different climatic conditions would be necessary to confirm the assumed quadratic productivity function for these crops.

Grain yield quality in terms of the nitrogen content of the grains is an additional important variable to characterize the quality of legume and cereal crops (Kemanian et al., 2007). The scatterplot of the nitrogen content in the yield compares results from the same soils in the dry and wet climate (Fig. 5h). The comparison showed no effect of climatic conditions or of the fertilization on the crop grain quality. Larger deviations from the 1 : 1 line were only visible for the soils from Dedelow and the crop pea under a dry climate and for soils from Bad Lauchstädt and crop winter rye under a wet climate (Fig. 5h). Nuttall et al. (2017) remarked that heat stress during the time of flowering and higher temperatures during the post-anthesis period of crops impact grain-size and milling yield. The impact of rising temperatures and increasing CO_2 concentrations in the atmosphere on yield quality could affect the nutritional quality and end use value (Asseng et al., 2019). The grain yield quality was reported to be influenced mainly by genetics, crop management and environmental conditions (Nuttall et al., 2017). Since in the present study, the crop management was similar, and the same cultivars were used, the altered climatic conditions seemed not to affect the quality of the yield in our crossed soil–climate experiment.

Table 1. Average values (of three lysimeters each) of cumulative evapotranspiration ($\sum$ET) for the whole observation period (2011–2017) and cumulative transpiration ($\sum ET_T$) and evaporation ($\sum ET_E$) for periods dominated by evaporation (E) or transpiration (T) for soils from Bad Lauchstädt (BL), Sauerbach (Sb), Dedelow (Dd) and Selhausen (Se) under a dry climate at BL and a wet climate at Se. The ET_T values were defined from the beginning of the vegetation period (April) until ripening/maturity of the fruit or seeds; the data for $\sum ET_E$ comprised the values from rest of the season. The differences of the cumulative values for the same soils between the sites BL and Se are denoted by $\Delta \sum$ET, $\Delta \sum ET_E$ and $\Delta \sum ET_T$.

Location		Se	BL	Se	BL	Se	BL	Se	BL
Soil		BL	BL	Sb	Sb	Dd	Dd	Se	Se
$\sum$ET	(mm)	4090.1	3490.8	4121.0	3406.8	3593.9	3316.7	3985.0	3323.0
$\sum ET_E$	(mm)	2102.5	1616.9	2110.3	1595.1	1941.7	1593.1	2228.2	1668.0
$\sum ET_T$	(mm)	1987.5	1873.9	2010.7	1811.7	1652.1	1723.7	1756.8	1655.0
$\Delta \sum$ET	(mm)	599.3		714.2		277.1		661.9	
$\Delta \sum ET_E$	(mm)	485.7		515.2		348.7		560.2	
$\Delta \sum ET_T$	(mm)	113.6		199.0		-71.5		101.8	

4 Conclusion

Lysimeter data from a Germany-wide lysimeter network (TERENO-SOILCan), where intact soil monoliths were moved to sites with contrasting climatic conditions, were used to analyse effects of soil and climate on agricultural ecosystems in a soil–climate crossed factorial design. In the wet climate, there was a net drainage which was larger for the coarser- than for the finer-textured soils. In the dry climate, a small negative net drainage (upward flux) was obtained when observing the long-term average for the whole period 2011–2017. In the wet climate, drainage dominated for all soils. When looking at shorter periods, negative values of monthly net fluxes were observed during the summer months at both sites.

During winter months, the soil water storage returned to a typical value, and drainage occurred when this value was reached. In the dry climate, this critical SWS was not reached in two soils after the growing season of 2015 in which the SWS was strongly depleted. The resulting insufficient refilling of the soil water storage capacity after a drought suggests that the precipitation during the following winter months was not sufficient to refill the soil so that no drainage took place. This lack of drainage had consequences for the upward water fluxes in the following growing seasons. Future studies about the impact of climate change, which in general are expected to increase the frequency and duration of droughts, on agro-ecosystem water balances and crop development should consider the long-lasting impact of droughts on the soil water balance and soil water fluxes that are carried over to following years. Results indicate that direct observation on the SWS will become increasingly important in environmental climate change studies, where changing climatic conditions could affect the SWSC. Longer-term monitoring data are needed to observe effects of impacts on soil properties.

Crops were more productive in terms of grain yield and used less water under drier climatic conditions. Plant development and a higher crop water use efficiency demonstrated that less plant available soil water did not go along with a decline of grain yield, because plants used the available soil water resources under such conditions more efficiently (e.g. by reduced soil evaporation). Results revealed in contrast to our hypothesis of a linear productivity function for some crops a quadratic productivity function and thus showed that plants can maximize their grain yield under an intermediate ET range in rainfed agriculture. However, longer time series are necessary to confirm the latter hypothesis of a quadratic productivity function of the corresponding crop. Our results suggest that despite the higher grain yield (quantity), climatic conditions seemed not to affect the quality of the yield, which might reflect a positive effect of the regional drier climatic conditions for crop production. The results of this study so far confirmed that typical soil water balance components, crop water use and especially the soil water storage dynamics undergo a substantial change when exposed to different climatic conditions.

The result further suggests that:

1. A new approach based on lysimeter mass data can enable the long-term monitoring of SWS changes at the pedon scale.

2. SWS dynamics were vulnerable to droughts and led to an insufficient refilling of the soil water storage capacity.

3. Crossed soil–climate experiments are useful to determine the impact of changing climatic conditions on the ecosystem water balances.

4. Crop water use efficiencies increased with reduced water supply.

The results herald the need to account for potential changes in soil water storage and plant reactions due to changes in climatic conditions and variability when trying to develop adaptation strategies in the agricultural sector.

Data availability. All data for the specific lysimeter and weather station (raw data) can be freely obtained from the TERENO data portal (https://teodoor.icg.kfa-juelich.de/ddp/index.jsp (last access: 4 March 2020; Kunkel et al., 2013), lysimeter station Bad Lauchstädt and Selhausen: SE_Y_03 and SE_Y_04). Climate data for the experimental station Bad Lauchstädt can be acquired upon request from Ralf Gründling. The processed data to support the findings of this study can be acquired also from the TERENO data portal (https://hdl.handle.net/20.500.11952/butt.metadata.handle/00000010; Groh, 2019).

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Competing interests. The authors declare that they have no conflict of interest.

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