1. Title page

Sequestering carbon in the subsoil benefits crop transpiration at the onset of drought

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2. Abstract

Increasing soil organic carbon is promoted as a negative emission technology for the agricultural sector with a potential co-benefit for climate adaptation due to increased soil water retention. Field-scale hydrological models are powerful tools to evaluate how the agricultural systems would respond to the changing climate in upcoming years and decades, to predict impacts, and look for measures that help decrease drought-driven crop stress under current and future climatic conditions. We quantified how different levels of soil organic carbon (SOC) additions at varied soil depths are expected to influence drought-induced transpiration reduction ($Tred_{dry}$) in maize cultivated in Switzerland. Parameterization of the model based on a pedotransfer function (PTF) was validated against soil moisture data from a long-term lysimeter experiment with a typical Swiss soil and the model was subsequently applied under climate forcing between 1981 until 2099 representative of three distinct climatic sites of Switzerland. We used the same PTF to indirectly assess the effects of SOC additions in different depths on soil hydraulic properties. We found a threshold in both added amount of SOC (2% added) and in the depth of sequestering that SOC (top 65cm) beyond which any additional benefit appears to be substantially reduced. However, adding at least 2% SOC down to at least 65 cm depth can reduce $Tred_{dry}$ in maize, i.e. increase transpiration annually, but mostly at the onset of summer drought by almost 40 mm. We argue that SOC increases in subsoils can play a supporting role in mitigating drought impacts in rain-fed cropping in Switzerland.

Keywords: climate change adaptation; water use efficiency; soil management; pedotransfer functions, simulation modeling; SWAP

3. Introduction

Over the last few decades, scientific studies have increasingly emphasized the need and explored potentials for soil carbon sequestration in agricultural soils to mitigate climate change (e.g. Lal (2001, 2004); Minasny et al. (2017); Smith et al. (2008)). In this context, other possible impacts of increasing soil organic carbon (SOC) on important soil functions and services have also been highlighted (e.g. on soil biodiversity, soil structure, soil water retention and infiltration capacity; see Lal (2004); Murphy (2015)). Management practices such as application of organic amendments (i.e. compost, manure, biochar), cover cropping, crop diversification and the adoption of conservation tillage systems are commonly considered beneficial for increasing SOC (Crystal-Ornelas et al., 2021). With an increase in soil organic carbon in quantity, quality and chemical diversity, soil communities are promoted and biotic-abiotic interactions are enhanced, with positive impacts on the formation and storage of soil organic matter (Zhang et al., 2021). Physical properties of the soil are altered directly by soil organic carbon increase and indirectly through the activity of soil fauna (e.g. Arthur et al. (2015); Rivier et al. (2022); Nemes et al. (2005); Rawls et al. (2004)). Soil structure has major influence on the natural soil water retention capacity, an essential regulating ecosystem service provided by soils that may play an increasingly crucial role in mitigating drought-induced limitations as climate change progresses (Liu et al., 2021). Soil texture also strongly affects how soil hydraulic properties respond to organic amendments, as shown by a meta-analysis from Edeh et al. (2020), who reported decreased hydraulic conductivity of sandy soils and increased the hydraulic conductivity of clayey soils after biochar additions. A recent meta-analysis performed for Europe has also shown that the adoption of organic amendments and "continuous living cover" benefit the soil water regulation functions (Blanchy et al., 2023).

With that in mind, the potential for achieving synergies between climate mitigation and adaptation seem promising. However, empirical evidence on benefits from increasing soil organic carbon for reducing drought limitations in crops is inconclusive. For example, Minasny and Mcbratney (2017) performed a meta-analysis with globally distributed soil data combined with the development of pedotransfer functions (PTFs) and found that 1% increase in SOC has a minor effect on available water capacity (AWC), with more pronounced differences in sandy soils than fine textured soils. Libohova et al. (2018), however, evaluated the effect of SOC on AWC using the National Cooperative Soil Survey (NCSS) Soil Characterization Database and found that a 1% increase in soil organic matter content increased AWC up to 1.5% times its weight, depending on soil texture and clay mineralogy. Also, a global metanalysis of 17 long-term field experiments conducted by Eden et al. (2017) found that plant available water increased significantly with the addition of organic material to the topsoil.

So far, only few model-based analyses have explored benefits of SOC increases on soil water availability systematically. Thereby, assumption on SOC influences on soil hydraulic properties were based on evidence from pedotransfer functions (PTFs). Feng et al. (2022) applied the crop model APSIM at a regional scale in China to model yield variability of maize and identified a statistically significant relationship between SOC and temperature-sensitivity of maize yields, suggesting that SOC contributes to climate resilience. A different model-based study design was implemented by Bonfante et al. (2020), who applied the SWAP model (Kroes et al., 2017) to 6 different Italian soils with assumed increased soil organic matter up to 2-4% in the topsoil. They found only minor increases in moisture supply capacity to be achieved with additional organic matter in the soil. In contrast to this, Ankenbauer and Loheide (2017), who applied a 1-D variably saturated groundwater flow model, found that increases in soil organic matter can contribute as much as 88 mm to transpiration, or 35 additional water-stress free days, during a dry summer. Discrepancies in these studies' findings may be attributable to differences in pedo-climatic conditions as well as to model setups and the chosen levels and depths of SOC increase.

A systematic analysis of the impacts of SOC increase on drought stress reduction depending on depth of SOC increase is lacking so far. It is thus the aim of this study to systematically evaluate and quantify the potential benefits of increasing SOC for drought limitations in a regional context not only under current, but also under projected future climatic conditions. As a study case, we chose to evaluate how changes on SOC to different depths affect the drought stress experienced by maize at the Swiss Central Plateau region, where agricultural land use dominates and for which region climate projections suggest a decrease in summer precipitation and an increase in winter precipitation as climate change progresses (CH2018, Kotlarski and Rajczak (2018)). Annual precipitation sums are expected to remain largely the same over the projection period until the end of the century, ranging from 997 mm in the southwest to 1013 mm in the northeast. As previous studies have shown, drought stress is already limiting grain maize productivity under current conditions (Holzkämper et al., 2013; Holzkämper et al., 2015b) and this limitation is expected to become more significant as climate change progresses. According to Holzkämper (2020), irrigation demands for grain maize might increase by up to 20% by the end of this century, in comparison with the reference period of 1981-2000, assuming that the duration of the growth season remains constant. If late-maturing varieties would be grown, given the possibility of an extended growth season with increasing temperatures, irrigation water demand may even increase by 40% (Holzkämper, 2020). This raises concerns about the availability of irrigation water in the Swiss Central Plateau, where reoccurring irrigation bans have challenged farmers more and more frequently in recent drought years (Bafu, 2019, 2016). Solutions to make Swiss production systems less reliant on supplementary irrigation are urgently needed.

4. Data and methods

To systematically evaluate the benefits of increasing soil organic carbon (SOC) for reducing drought limitations on a typical agricultural soil in the Swiss Central Plateau, we apply a field-scale agro-hydrological model that is deemed a suitable tool to interpret interactions between crops and the environment (Maharjan et al., 2018). The soil component of the model was parameterized using a recently developed pedo-transfer function and the model setup is validated against measurements of soil moisture dynamics in two lysimeters of a lysimeter station. Subsequently, the model is applied based on downscaled climate projection data in combination with scenarios of soil carbon increases.

4.1 Agro-hydrological modelling with SWAP

The Soil Water Atmosphere Plant model (SWAP, version 4.0.1) (Kroes et al., 2017) is a physically based agro-hydrological model that simulates the transport of water, solutes, and heat in the unsaturated (vadose) zone and optionally the upper part of the saturated (groundwater) zone with the upper boundary condition defined by atmospheric conditions. Major arable crops and grasslands can be explicitly simulated in SWAP via incorporation of the WOFOST (WOrld FOod STudies, De Wit et al. (2019)) model or by using a simple crop module.

In interaction with the crop development, the model simulates the heat and solute transport dynamics of variably saturated soils by employing the Richards equation in the vertical direction, including a sink term for root water uptake:

$$C(\mathrm{h})\frac{\partial \mathrm{h}}{\partial t} = \frac{\partial\left[\mathrm{K}(\mathrm{h})\frac{\partial(\mathrm{h}+z)}{\partial z}\right]}{\partial z} - S_a(\mathrm{h}) \qquad [1]$$

where C(h) (cm^{-1}) is the specific water capacity, the derivative of the soil water retention function θ(h), which describes the relation between water content θ (cm^3 cm^{-3}) and soil water suction h (cm, defined as positive at unsaturated conditions), t (d) is time, K(h) (cm d^{-1}) is the hydraulic conductivity as a function of h, z (cm) is the vertical spatial coordinate (negative downwards), and S_a(h) (d^{-1}) is a sink term representing the rate of soil water extraction by plant roots.

The relationship θ(h) and K(h) are defined by the van Genuchten (1980) - Mualem (1976) (VGM) equations:

$$\theta(\mathrm{h}) = \theta_r + \frac{(\theta_s - \theta_r)}{[1 - |\alpha \mathrm{h}|^n]^m}$$

$$\mathrm{K}(\mathrm{h}) = \mathrm{K_s}\Theta^l\left[1 - \left(1 - \Theta^{\frac{1}{m}}\right)^m\right]^2 \qquad [2]$$

where θ_s and θ_r are the saturated and residual soil water content (cm^3 cm^{-3}), α (cm^{-1}), n, m (m = 1-1/n), and l are empirical shape parameters, K_s is the saturated hydraulic conductivity (cm d^{-1}) and the relative degree of saturation, Θ, is expressed as $\Theta=(\theta-\theta_r)/(\theta_s-\theta_r)$.

In our study, the model used crop properties and atmospheric conditions on a daily basis to calculate the potential evapotranspiration based on the Penman-Monteith equation. Water stress was evaluated according to the reduction function by Feddes (1978), with the optimal root water uptake in the h ranges of -325.0 cm (h_{3H}) or -600 cm

(h_{3L}) to -30 cm (h_2), oxygen stress linearly increasing for h higher than -15 cm (h_1) and drought stress linearly increasing for h smaller than -8000 cm (h_4). The crop growth module considers that the actual transpiration can be reduced by drought (too dry), $\alpha_d (z)$, lack of oxygen (too wet), $\alpha_o (z)$, or too saline conditions (physiological drought), $\alpha_s (z)$, which factors are known to reduce crop growth. The actual root water flux, $S_a(z)$ (d^{-1}), is then a function of all considered stresses:

$$S_a(z) = \alpha_d(z)\alpha_o(z)\alpha_s(z)S_p(z) \quad [3]$$

where $S_p(z)$ is the potential root water extraction rate at a certain depth. The actual transpiration, T_a (cm d^{-1}), is calculated by integrating the root water flux over the root zone:

$$T_a = \int_{-D_{root}}^{0} S_a(z)\partial z \quad [4]$$

where D_{root} is the root layer thickness (cm).

In our simulations, we did not consider stresses caused by saline conditions and focused on the drought-induced transpiration reduction ($Tred_{dry}$) as an indicator of drought stress during the cropping period.

4.2 Climate data of three distinct study sites from measured and projected scenarios

Typical Swiss agricultural conditions were evaluated at three distinct sites distributed along the Swiss Central Plateau (the main agricultural production zone in Switzerland): Nyon-Changins (CGI), Zürich-Reckenholz (REH), and Wynau (WYN). Measured climatic variables from meteorological stations were obtained from MeteoSwiss. Table 1 contains annual mean values of the meteorological variables required by SWAP, while Figure 1 presents their seasonal variation. While the three sites have similar altitude, on average, the CGI site has the driest and warmest climate, with higher solar radiation and wind speed. WYN is on average the wettest and coldest. In all sites the rainfall is relatively well distributed during the year, with higher precipitation, temperature and solar radiation in the summer season.

Table 1 Site description and climatic variables based on mean ± standard deviation values observed between 1981 and 2022 from MeteoSwiss.

	Meteorological station		
	CGI (Changins)	REH (Reckenholz)	WYN (Wynau)
Altitude (m)	455	443	422
Latitude	46.4 N	47.4 N	47.3 N
Longitude	6.2 E	8.5 E	7.8 E
Rainfall (mm y^{-1})	997 ± 147	1013 ± 146	1117 ± 188
T_{min} (°C)	6.5 ± 5.7	5.1 ± 5.9	5.0 ± 5.9
T_{max} (°C)	14.8 ± 7.8	14.3 ± 8.0	14.3 ± 8.2
Solar radiation (MJ m^2 d^{-1})	12541.5 ± 7035.4	11372.0 ± 6738.6	11437.9 ± 6865.4
Vapour pressure (kPa)	0.98 ± 0.36	0.98 ± 0.38	0.99 ± 0.38
Wind speed (m s^{-1})	2.4 ± 0.2	1.8 ± 0.3	1.7 ± 0.3

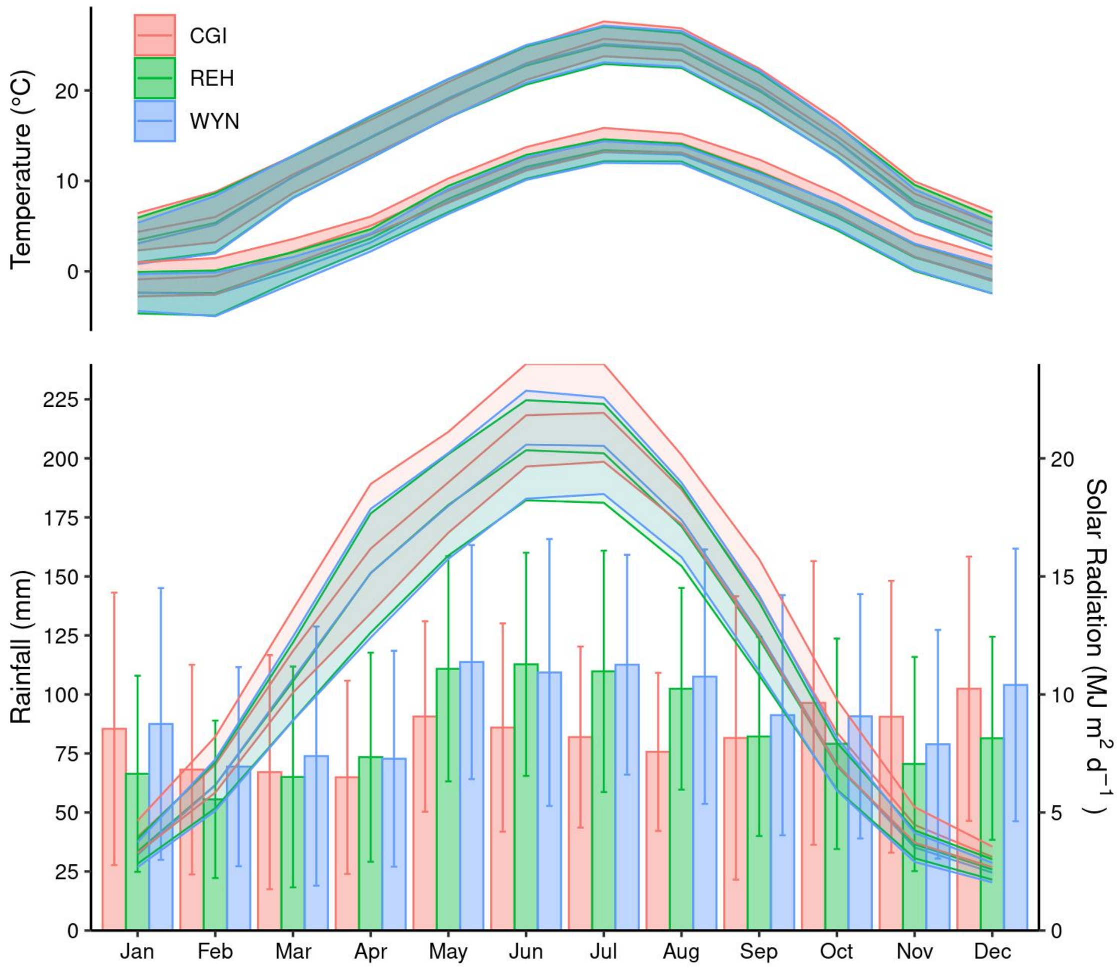

Figure 1 Seasonal variability of climatic variables considering monthly mean ± standard deviation (shades and bars) values observed at the meteorological stations between 1981 and 2022. Rainfall corresponds to monthly sums, while other variables represent daily values averaged by month. Minimum (bottom lines) and maximum (upper lines) temperatures are presented.

Future scenarios were evaluated using climate projections developed by the National Centre for Climate Services (NCCS) in Switzerland (Kotlarski and Rajczak, 2018). The dataset contains transient daily time series for the period 1981-2099 for several variables at individual Swiss stations (DAILY-LOCAL), produced by applying a statistical downscaling and bias-correction method (Quantile Mapping, QM) to the original output of all EURO-CORDEX climate model simulations employed in CH2018 (Kotlarski and Rajczak, 2018). From all available projections with different

Representative Concentration Pathways (RCP), we selected the ones that presented the dataset with all required input variables for SWAP, as listed in Table 1. In total, we used 22 projections for RCP8.5, 17 for RCP4.5, and 8 for RCP2.6. For more details about selected model chains, see Supplementary Material (Section S1). Figure 2 presents an overview of the projected climate variables for the summer (JJA) and winter (DJF) months during the baseline (1981-2020), mid-century (2031-2060) and end-of-century (2081-2099) periods for each of the RCP8.5. More details about the other RCPs as Supplementary Material (Section S2). With the most pessimistic assumption about the evolution of greenhouse gas emissions (RCP8.5), climate projections estimate lower precipitation, higher temperature and higher solar radiation for future summers, while they predict higher precipitation, higher temperature and lower solar radiation for winters at the end of the century.

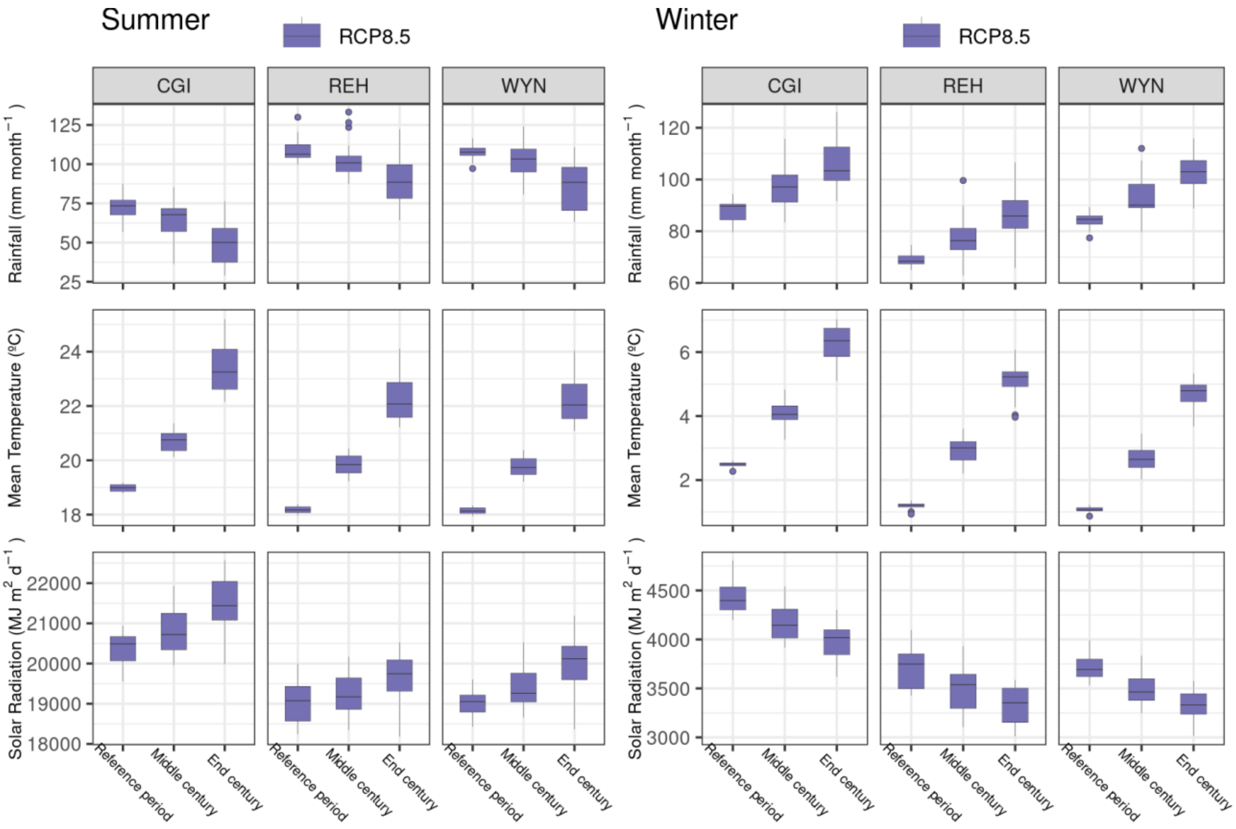

Figure 2 Summary of climatic variables considering monthly mean values at the stations Changins (CGI), Reckenholz (REH), and Wynau (WYN) for the projections RCP8.5. Summer was considered as the months June, July and August, winter corresponds to December, January and February. Reference period: 1981-2020, mid-century: 2031-2060, end-of-century: 2071-2099. Rainfall corresponds to monthly sums, mean temperature is the mean between maximum and minimum temperature per day, averaged by month, solar radiation corresponds to daily values averaged by month.

4.3 Model reference data and setup

Reference information on soil water dynamics at four different depths (10, 30, 60, and 90 cm) were available from lysimeters of 135cm depth and 1m^2 surface area at the lysimeter facility of Agroscope Zürich-Reckenholz (Prasuhn et al., 2016). Soil moisture was monitored from 2009 to 2022 using frequency domain reflectometry sensors (FDR; ThetaProbe ML2x, Delta-T Devices) at the depths of 10, 30, 60, and 90 cm. In each of the lysimeters two identical sensors were installed at each depth with a time resolution of one hour. We utilize the data of two lysimeters that contain similar soil monoliths from a typical agricultural soil nearby (Loamy-silty Cambisol above ground moraine (Fao, 2015), see Table 2 for the soil profile description). The monoliths have a 15 cm layer of purified quartz sand and gravel at the bottom that help facilitate free drainage.

For the model setup, the measured physical and chemical soil parameters (Table 2) were used in combination with the pedotransfer function (PTF) developed by Szabó et al. (2021), using the R package in which the euptfv2 is implemented (Weber et al., 2020). The euptfv2 is a Random Forest-based PTF with various options for inputs and output parameters, and has proven to be one of the most accurate PTFs to estimate soil hydraulic properties for Europe when tested on diverse datasets (Nasta et al., 2021). As the standard setup for all simulations, we used option ‘PTF02’, which requires the depth of the soil layer, soil texture, and soil organic carbon content (SOC) as input, and estimates the VGM parameters for the soil water retention [$\theta(h)$] and hydraulic conductivity [$K(h)$] functions (Eq. [2]).

Table 2 Soil physical and chemical properties of the evaluated typical Swiss agricultural profile at the Lysimeter facility at Agroscope Reckenholz. SOC: soil organic carbon, BD: bulk density, PD: particle density, CEC: cation exchange capacity. Soil class and horizon description according to Prasuhn et al. (2016).

Horizon	Depth cm	Clay %	Silt %	Sand %	SOC %	BD g cm^{-3}	pH_{H2O} -	pH_{CaCl2} -	PD g cm^{-3}	$CaCO_3$ %	CEC cmol+ kg^{-1}
Ahp	0-25	25	50	25	1.48	1.36	6.8	6.4	2.63	0.1	16.2
Abcn	25-32	24	54	22	1.09	1.44	7.1	6.6	2.68	0.2	15.67
Bcn(g)(x)	32-65	31	50	19	0.43	1.44	7.2	6.5	2.7	0.1	17.61
Bg	65-85	33	46	21	0.32	1.44	7.5	6.6	2.7	0.1	18.77
BCg	85-105	19	61	20	0.10	1.39	8.6	7.7	2.7	40.2	10.93
Cg	105-135	18	65	17	0.02	1.61	8.6	7.8	2.71	54.4	7.49

Table 3 presents the parameters of Eq. [2] at the evaluated soil profile from the Lysimeter station, calculated using the chosen PTF. The soil water retention and hydraulic conductivity curves are visualized in Figure 3.

Table 3 Soil hydraulic parameters calculated using the euptfv2 at the original soil profile, considering option 'PTF02' that uses soil texture, soil carbon content and soil depth as input.

Soil	Layer	Depth cm	θ_r cm^3 cm^{-3}	θ_s cm^3 cm^{-3}	α cm^{-1}	n -	K_s cm d^{-1}	l -
Reckenholz	1	0-25	0.053	0.483	0.034	1.215	35.61	-1.59
	2	25-32	0.038	0.471	0.037	1.193	14.78	-0.70
	3	32-65	0.059	0.435	0.015	1.196	10.41	-0.62
	4	65-85	0.078	0.417	0.014	1.196	4.41	-1.23
	5	85-105	0.034	0.422	0.011	1.370	3.34	0.23
	6	105-135	0.026	0.424	0.005	1.441	1.77	0.09

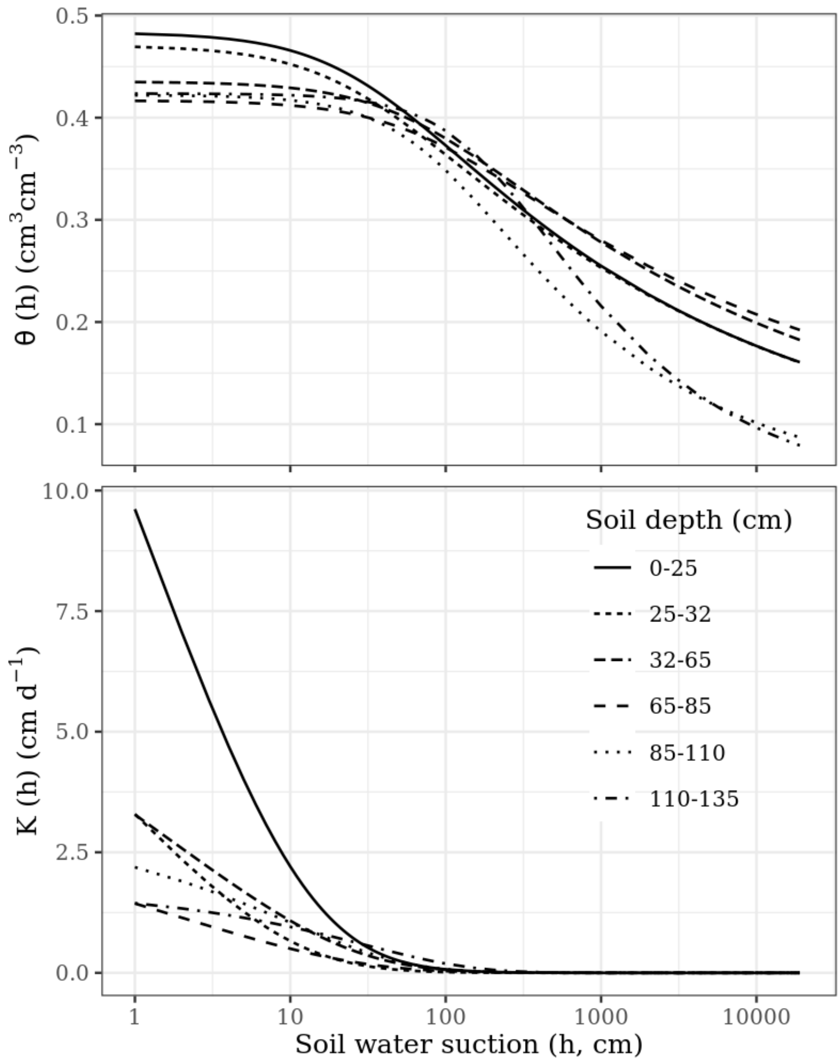

Figure 3 Soil water retention (θ) and soil hydraulic conductivity (K) as function of the soil water suction (h) at the evaluated soil profile estimated by the euptfv2 (option ‘PTF02’).

The validation of SWAP with the lysimeter information included three cropping periods with grain or silage maize in 2009, 2015 and 2020, with annual precipitation of 1018.9, 831.5 and 855.2 cm, respectively. Daily time step was adopted and vertically, the top soil layer up to 65 cm was discretized using 1.0 cm sub-compartments, while subsequent layers were discretized with 5 and 10 cm sub-compartments. The boundary condition was set to ‘free outflow at soil-air interface’, which is considered as a valid option for lysimeters. The evapotranspiration was calculated using weather data and application of the Penman-Monteith equation. No macropore flow, lateral drainage or solute dispersion was simulated. For the validation, the daily averaged values of measured soil water content at each replicate sensor and depth (eight time series per lysimeter) were compared to the modeled values by SWAP. As validation metrics, we used the root mean square error (RMSE) and the Pearson correlation (*r*). See Supplementary Material S3 for details on model setup.

4.4 Design of simulation experiments

In the absence of consistent and comparable data from long term and holistic studies that account for the impacts of management on soil hydraulic properties, pedotransfer functions (PTFs) are seen as a suitable choice to systematically account for linkages between SOC and soil hydraulic properties. We thus used the chosen PTF to systematically capture secondary effects of SOC instead of directly inferring the effects of specific drivers of change on the soil hydraulic properties due to the uncertain interaction effects between SOC, soil type, climate and management.

We assumed that management improvements have led to increased SOC from the beginning of the simulation period and that SOC remained stable over the simulation period, thereby testing different scenarios of successful carbon sequestration. The model parametrization included three distinct depth scenarios: i) changes in SOC occur only within the top 0-25 cm, ii) changes in SOC occur to 0-65 cm depth and, iii) changes in SOC are achieved for the entire soil profile. In terms of SOC change, we simulated the addition of up to 4% SOC to current SOC levels by 1% increments in the (i) and (ii) depth scenarios, but applied reduction factors of 0.8 and 0.6 for the 65-105 cm and 105-135 cm depths respectively in depth scenario (iii). This approach considers that obtaining greater SOC via management likely affects the topsoil more than the deeper soil layers. The outlined depth and SOC level scenarios are listed in Table 4 for easier comprehension.

It should be emphasized that the levels of SOC in the soil are dependent on several factors including land use and management, climate, geomorphology, which were considered as empirical relationships in this work.

Table 4 Description of %SOC levels added per depth and final values of SOC considering the described scenarios i), ii), and iii). Shaded values represent the layers where changes on SOC were applied.

	Effective depth of changes (cm)		i) 0-25	ii) 0-65	iii) 0 -135
Scenario	Soil depth (cm)	SOC added (%)	SOC final (%)		
0%	0-25	0	1.48	1.48	1.48
	25-32	0	1.09	1.09	1.09
	32-65	0	0.43	0.43	0.43
	65-85	0	0.32	0.32	0.32
	85-105	0	0.10	0.10	0.10
	105-135	0	0.02	0.02	0.02
1%	0-25	1	2.48	2.48	2.48
	25-32	1	1.09	2.09	2.09
	32-65	1	0.43	1.43	1.43
	65-85	0.8	0.32	0.32	1.12
	85-105	0.8	0.10	0.10	0.90
	105-135	0.6	0.02	0.02	0.62
2%	0-25	2	3.48	3.48	3.48
	25-32	2	1.09	3.09	3.09
	32-65	2	0.43	2.43	2.43
	65-85	1.6	0.32	0.32	1.92
	85-105	1.6	0.10	0.10	1.7
	105-135	1.2	0.02	0.02	1.22
3%	0-25	3	4.48	4.48	4.48
	25-32	3	1.09	4.09	4.09
	32-65	3	0.43	3.43	3.43
	65-85	2.4	0.32	0.32	2.72
	85-105	2.4	0.10	0.10	2.5
	105-135	1.8	0.02	0.02	1.82
4%	0-25	4	5.48	5.48	5.48
	25-32	4	1.09	5.09	5.09
	32-65	4	0.43	4.43	4.43
	65-85	3.2	0.32	0.32	3.52
	85-105	3.2	0.10	0.10	3.3
	105-135	2.4	0.02	0.02	2.42

To quantify the impacts of increasing SOC on drought stress in maize under climate change, SWAP was applied to the 22 climate projections at the three sites Changins (CGI), Reckenholz (REH), and Wynau (WYN) in combination with the scenarios of SOC increase listed in Table 4. We assumed grain maize to be sown on 6th May (DOY 126) and harvested on 17th Oct (DOY 290) as registered in the Swiss variety trial data for a medium-late variety type (Agroscope, 2023). The bottom boundary condition was set as free drainage, representing a soil profile with deep groundwater levels. For details of general SWAP parameterization see Supplementary Material S3.

All simulations considered rain fed conditions and were performed using the simple crop growth module for a static crop, which simulates a fixed development of leaf area index and rooting depth, independent of climatic conditions, in order to keep the cropping period fixed for all scenarios. In this study we worked with 165 days of crop growing period; the crop component's parameterization is described in Supplementary Material S4.

Overall, we conducted a total of 990 simulation runs (5 levels of SOC × 3 soil depths × 3 sites × 22 climate projections) for the period 1981-2099, and used cumulative amounts of drought-induced transpiration reduction ($Tred_{dry}$) as an indicator of drought stress during the cropping period. The 10-year moving average of $Tred_{dry}$ was calculated to represent decadal changes and exclude interannual variability. The range of $Tred_{dry}$ values among the available climate projections were represented by the 0.05 quantile ($q_{0.05}$) and the 0.95 quantile ($q_{0.95}$) as upper and bottom boundaries, respectively. The difference between management scenarios in terms of crop transpiration, defined as the average transpiration gain (ATG) with SOC increase, was calculated as the difference between the scenario with no addition of SOC (0%) and the one with the maximum addition of SOC (4%).

5. Results

5.1 Model validation

Using the soil hydraulic parameters from Table 3, we simulated soil water content in the lysimeter soil profiles and compared them with moisture data measured by FDR sensors. The lumped values of the two lysimeters, considering all maize cropping periods (2009, 2015, and 2020), all depths (10, 30, 60, and 90 cm) with duplicated sensors, resulted in a median ($q_{0.5}$) RMSE of 0.066 cm^3 cm^{-3} ($q_{0.05}$=0.050 cm^3 cm^{-3}, $q_{0.75}$=0.098) and correlation median correlation *r* of 0.79 ($q_{0.05}$=0.68, $q_{0.75}$=0.84). In general, the simulations were more accurate for the deeper layers as compared to the topsoil. At 10 cm, the RMSE was on average 0.11 cm^3 cm^{-3}, whereas it was 0.04 cm^3 cm^{-3} at the bottom.

5.2 Effect of increasing SOC on the soil hydraulic properties and soil water balance

The effects of adding different amounts of SOC at different soil layers (Figure 4) are reflected in PTF estimates of soil hydraulic properties with updated SOC contents. The “0%” line, corresponding to the VGM parameters in Table 3, represent the properties of the different soil layers with current SOC. For the soil water retention curve, the effects of the increase in SOC reflected an estimated increase in pore space, whose expression varied with soil depth and added SOC. In the topsoil, the differences between the addition of 1% and 4% SOC were not as remarkable as in the subsoil layers, where an addition of 1% SOC lead to a substantial increase in estimated pore space. For saturated hydraulic conductivity, the overall trend was a reduction in conductivity with the increase in SOC, with the biggest contrasts found in the topsoil.

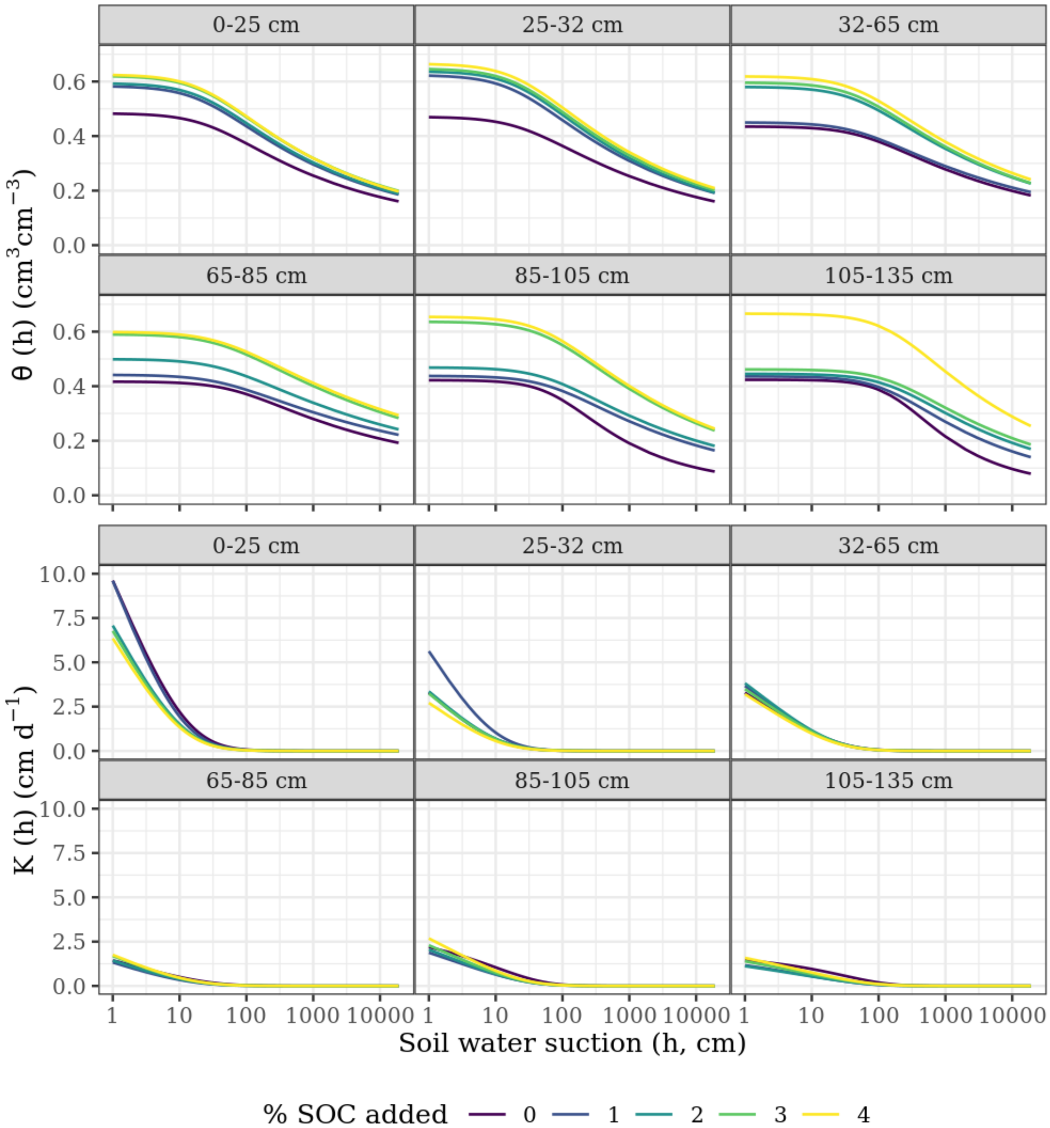

Figure 4 Effects of SOC increase on the soil water retention (θ) and soil hydraulic conductivity (K) as function of the soil water suction (h) as predicted by euptfv2, option 'PTF02'.

Considering effects of adding SOC at different soil depths, Figure 5 presents an overview of the transient simulations between 1980 and 2099 with the most unfavorable climate scenario projections (RCP8.5). For each year of simulation, a range of values of $Tred_{dry}$ was generated by the 22 climate projections, which are being represented by a band defined by the lines $q_{0.05}$ and $q_{0.95}$ quantiles, and the $q_{0.5}$ quantile (median) is represented by a line within that band. The average transpiration gain (ATG) line is the difference between the median ($q_{0.5}$) values of the original Reckenholz soil profile (i.e.

0% SOC addition) and the one that had 4% SOC added. The ATG can be interpreted as the amount of seasonal transpiration gained in response to increased SOC. The absolute increase in $Tred_{dry}$ comparing the reference period with the end of the century was on average 269, 207, and 269 mm at CGI, REH and WYN, respectively. Additional results considering other Representative Climate Projections (RCP 2.6 and 4.5) are presented in the Supplementary Material (Section S5).

Figure 5 Transpiration reduction due to drought stress ($Tred_{dry}$) (left axis, green band) for actual and future climate conditions considering different levels of SOC increase in the soil at different effective soil depths; and average transpiration gain, ATG, (right axis, colored lines) between 0 and 4% addition of SOC. Climate projections

considered the RCP8.5 pathway and were averaged for every 10 years. The green shaded area of $Tred_{dry}$ refers to the values between (dotted) quantiles $q_{0.05}$ and $q_{0.95}$ of the climate projections. ATG is interpretable as average seasonal gain in transpiration due to SOC increase, and ATG slope refers to the slope of the ATG line between 0 and 4% SOC addition.

According to the simulated scenarios, the main driver of the absolute values of $Tred_{dry}$ is the climate, with more drought stress under the climate of the drier site (CGI) and very similar stress levels under the climate of the other two sites, REH and WYN, that are wetter and appear to be somewhat resembling. There was a clear tendency of increased stress towards the end of the century, driven by more unfavorable climatic conditions during the cropping period (Figure 2). The ATGs were very similar amongst the three considered climates, with maximum values around 60 mm $year^{-1}$, and slightly higher in the CGI climate. The *ATG slopes* calculated between the beginning and the end of the century were higher at REH and WYN, which are the sites with less water stress under current conditions. This is an implication of not considering a gradual build-up period for increased SOC, but considering the same levels of SOC addition for the entire simulation period.

The simulations were performed considering the addition of SOC down to three different depths (25, 65, and 135 cm). The addition of SOC to the top 25 cm seems to have a modest effect on $Tred_{dry}$. The effects of increasing SOC all the way to 135 cm are the greatest, but are comparable to the intermediate option of adding SOC till 65 cm depth. In general, adding 2% SOC already lead to considerable reduction in $Tred_{dry}$, and is a more realistic, easier-to-implement alternative to adding 4% SOC.

5.3 Detailed soil water dynamics and drought stress over the cropping period

Figure 6 depicts, as an example, how the soil moisture profile develops and how the ATG in moisture deficit builds up during the simulated 2015 cropping year at the REH site, with the different increased SOC levels in the entire soil profile (depth scenario iii). The addition of SOC leads to a clear pattern of increasing soil water retention.. The blue line depicts the daily simulated crop transpiration deficit ($Tred_{dry}$) of the 0% added SOC scenario, while the black lines depict the same obtained for the relevant depth and SOC addition scenario in each plot. Their difference, when cumulated for the year, yields the transpiration deficit ATG for the given year and scenario. The most remarkarble seasonal ATGs were observed in the beginning of the cropping season, and could be linked to increased soil water retention capacity combined with the availability of water in that season. According to Figure 4, increased SOC content generally yielded increased soil water retention capacity relative to the base scenario of no SOC addition. In the early cropping season this increased capacity is capitalized on in the form of retaining more water in the system by the end of the recharge-period in the wet and cold winter and spring season. The simulated extra amount of water is clearly demonstrated in Figure 6. During the early part of the growing season, this excess water then becomes available to the crop, dampening the effects of any drought-stress, or at least delaying its onset. The soil will also not dry out to the same degree during the later half of the season, or at least not to the same depth. Similar results for the other evaluated sites are presented in the Supplementary Material (Section S6).

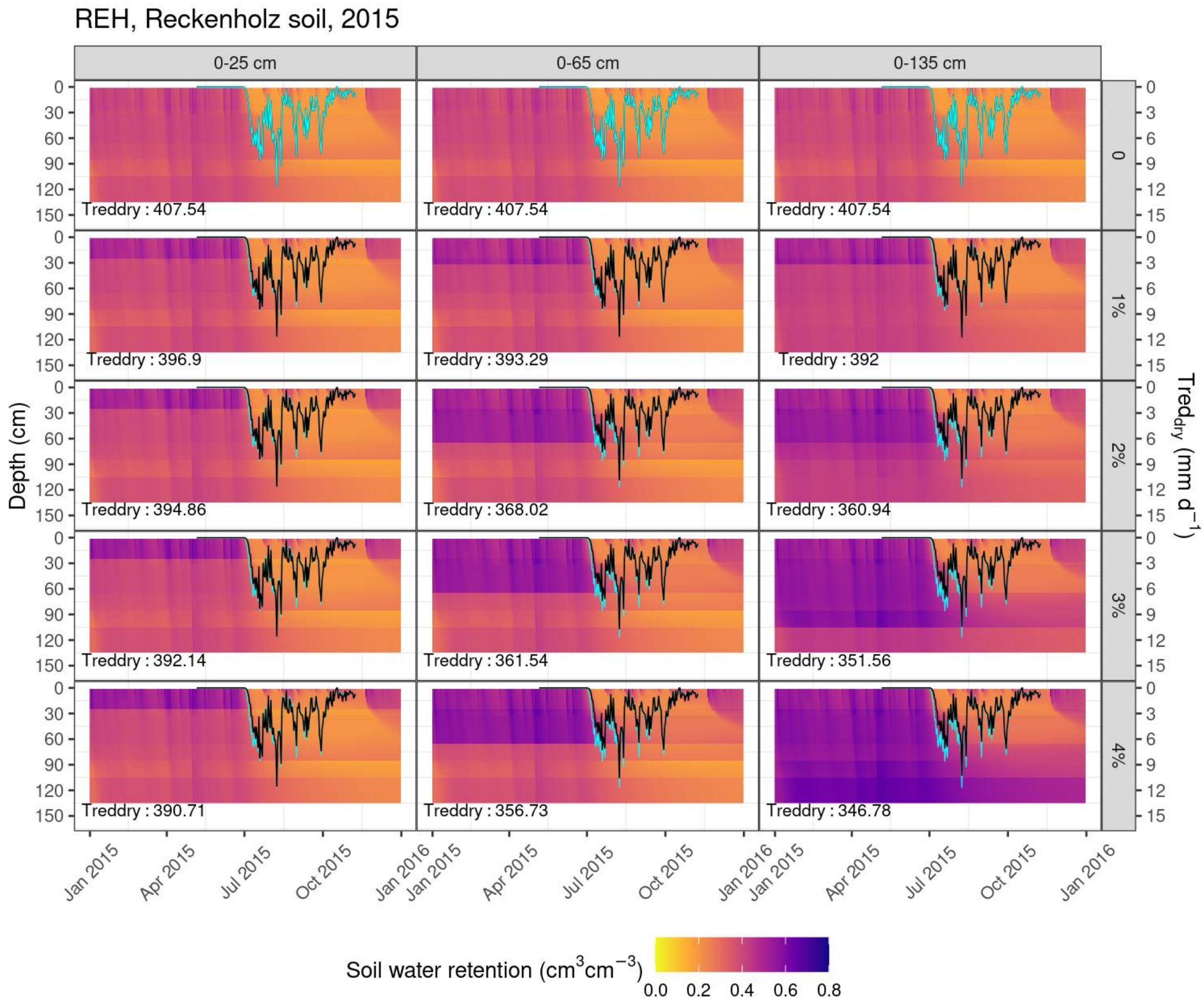

Figure 6 Detailed profile of soil water content (left axis) and Tred$_{dry}$ (right axis, black lines) according to the different added SOC levels at the Reckenholz site (REH) in the year of 2015. The blue line represents Tred$_{dry}$ for the original soil profile (0% SOC). When cumulated for the year, their difference yields the annual ATG in crop transpiration deficit that is due to the addition of carbon to the soil.

6. Discussion

6.1 Increasing soil organic carbon reduces drought stress in maize

We observed that according to the predictions of the used PTF, an increase of SOC has a small effect on, but generally decreases soil hydraulic conductivity (Figure 4). This may be counter-intuitive in that textbook knowledge connects greater SOC content with better soil structure formation, greater porosity, and in turn to enhanced water transport properties (hydraulic conductivity) (Nemes et al., 2005). However, several studies have now emerged that correlated greater SOC content with lower hydraulic conductivity. These studies include both experimental data and the mining of several extended databases using machine-learning (Nemes et al., 2005; Wang et al., 2009; Jarvis et al., 2013; Larsbo et al., 2016). The rationale behind this notion is that when SOC content increases, there is enhanced porosity, but the tortuosity of conductive pathways may increase due to enhanced microbial activity and the formation of more complex aggregates, resulting in better water retention but reduced hydraulic conductivity. Some of these authors noted increased predicted water retention in the effective porosity (i.e. the range between field capacity and saturation), which supports the proposed notion.

Results from this simulation study suggest that increases in SOC would generally decrease drought stress in maize cultivated on a typical agricultural soil in Switzerland. The summer season precipitation amount at the evaluated sites is expected to be decreased by around 60-65 mm till the end of the century (Figure 2). In this scenario, a 2% addition of SOC can reduce drought stress of maize by 10.5 to 40 mm during the cropping season and potentially compensate part of the rainfall reduction with climate change. Bonfante et al. (2020) suggests that the effect of SOC on moisture supply capacity should be evaluated in more climatic zones in order to obtain a broader picture of its potential impact. What we observed in this work was that the degree of decrease in $Tred_{dry}$ was only minimally dependent on regional climatic conditions, with the wettest site (WYN) benefitting least from the SOC increases under current climate conditions. As conditions get drier, as projected with climate change for the Swiss Central Plateau, the transpiration gain increases, but reaches a maximum at 60 mm with SOC increase down to 135 cm.

Our study suggests minor benefits of increasing SOC in the topsoil (maximum ATG reached is 15 mm, Figure 5). However, if SOC was increased down to at least 65 cm, this beneficial effect can be considerably higher (maximum ATG reached is 45 mm, Figure 5). Overall, the maximum ATG of $Tred_{dry}$ quantified in this study was 60 mm (at the end of the century, with SOC increase down to 135 cm), suggesting that without supplementary irrigation, seasonal crop transpiration can be up to 60 mm greater with increased SOC, compared to the reference situation. This amount is comparable to 1-2 irrigation dosages and makes up for roughly 30% of the average theoretical irrigation water demand estimated by Holzkämper (2020) for the region between Wynau (WYN) and Changins (CGI). The productivity gain to be achieved will strongly depend on the period in the cropping cycle when this extra water will be available. Considering that transpiration benefits are greatest at the onset of drought during early summer (Figure 6), the productivity gains may be particularly high if the effect coincides with the critical reproductive phase of the crop. This might imply that transpiration gains achieved with increases in SOC have a significant potential to increase yield stability, particularly in situations where and when irrigation is not an option.

The positive slopes of calculated ATGs of $Tred_{dry}$ (i.e. transpiration gained with SOC increase) in Figure 5 suggest that the benefits of SOC additions could slightly increase with projected future climate change – especially at WYN, the least water-limited site under current conditions. At the driest site, CGI, the ATG (i.e. benefit of SOC increase) reached under current climatic conditions is roughly at the same level as it is at WYN at the end of the century. These findings imply that the benefits of SOC accumulation may increase as water input (precipitation) during the cropping period decreases over time. However, there appears to be a threshold beyond which benefits are not seen as $Tred_{dry}$ further increases (the *ATG slope* in Figure 5 decreases from the wettest to the driest site). The benefit of "extra water availability" comes from the balance of two elements: available water and available storage capacity. It appears that the available storage capacity component is enhanced by the addition of some SOC (i.e. 2% addition in our simulations), but the system becomes water-limited by the end of the century. The extra storage capacity that additional SOC may yield will not be filled up by the actual water input, and the potential extra benefit cannot be realized. The within-year occurrence of the same phenomenon is observable in Figure 6. The biggest reduction in $Tred_{dry}$ occurs in the beginning of the cropping season, when the increased retention capacity was present at the same time when ample amount of water was recharging the system during and after the cold, rainy season, with little or no plant water uptake.

A similar balance is likely to apply when the outcome of a 135 cm deep application of added SOC is interpreted. When simulating SOC addition to 135 cm depth vs. only 65 cm, the added benefit in terms of reduced crop $Tred_{dry}$ appears to be limited. We argue that while some excess water storage capacity is simulated, there is little actual benefit realized from that, given the reduced amount of predicted precipitation by the end of the century. In addition, few, if any, crop roots reach that depth, which means that the only way the crop has direct benefit from water stored in the deeper soil layers in the growing season is if water redistributed upwards via capillary and vapor transport.

6.2 Possibilities to increase soil organic carbon

Results from our study suggest that the beneficial effects of increasing SOC are small if SOC is only increased in the top-soil (0-25 cm), but become more significant if SOC is increased to only 65 cm depth by at least 2%. We assumed that such SOC increases can be achieved, while different management adaptations and combinations thereof may be suitable to reach this target. Commonly considered strategies to increase SOC include additions of organic amendments, planting of deep-rooting crops, cover-cropping, intercropping, mulching with organic material, retaining crop residues in the field and reduced tillage or no-till (Topa et al., 2021; Ipcc, 2019). No-till or reduced tillage decreases the carbon oxidation process and soil disturbance with the loss of soil organic carbon and nutrient availability (Modak et al., 2019; Kan et al., 2020). Also, Angers and Eriksen-Hamel (2008) found that tillage affects the distribution of SOC over the depth of the soil profile with important implications in crop water availability. A meta-analysis on effects of tillage on SOC (Krauss et al., 2022) has shown that it is not uncommon that depletion in SOC of a subsoil layer co-occurs with increased SOC levels in the topsoil. We tested this with the particular soil and PTF used in our study, and found that the hydrological effects of reducing SOC at the depth of 25-32 cm were almost identical to the scenario in which the same amount of SOC increase in the depth of 0-25 cm was simulated but without subsoil SOC depletion (Figure 5). We emphasize that, from the point of view of water availability to plants with deep roots, management strategies should aim at increasing SOC content deeper than only in the topsoil.

According to Bai et al. (2019), reduced tillage or no-till increases SOC mostly in the top 10 cm and also in the sub-soil below 50 cm. The same study found that cover-cropping could increase SOC down to 70 cm depth. Incorporation of perennial grasses into crop rotations could help increase SOC to 60 cm depth, beyond the plough layer

(Carter and Gregorich, 2010). Evidence of this under Swiss conditions was provided by Guillaume et al. (2021); Guillaume et al. (2022). Overall, such strategies were found to be most beneficial to SOC accumulation near the soil surface (Bai et al., 2019). One management operation that could effectively contribute to an accumulation of SOC in deeper soil layers is deep ploughing (Alcántara et al., 2016). However, when the soil is loosened the SOC oxidation process is enhanced, as well as erosion may be triggered, which has to be accounted for when planning such interventions.

We have tested the scenario of incorporating extra amount of SOC in the soil down to a depth of 135 cm. This is a scenario that would require similar strategies as the previously discussed scenario, but it is likely rather difficult to implement, especially with greater amounts of SOC stored. Our study showed that in terms of water-availability to the (maize) crop, this scenario has little extra benefit to offer over the scenario of having extra SOC sequestered to 65 cm depth. Hence, any investment in sequestering SOC into such depths should not be driven by high expectation of hydrological benefits.

6.3 Limitations and further work

Our study, as well as previous modelling studies exploring impacts of SOC additions on soil water availability (e.g. Ankenbauer and Loheide (2017), Bonfante et al. (2020), Feng et al. (2022)), build on pedotransfer functions that are believed to be best in estimating soil hydraulic parameters for the study area based on levels of SOC and other soil properties. The selection of PTFs, however, may play a crucial role in the outcome of simulated scenarios. While recent studies confirm the validity of the equations used (e.g. Nasta et al. (2021); Wagner et al. (2004)), uncertainties in derived estimates may still be large (Fatichi et al., 2020). PTF structure may also have an influence in that more advanced (aka. “better”) PTFs are usually products of refined machine learning algorithms that may produce strong results in general but may have different estimation qualities in different parts of the data domain. Since such local performance is rarely evaluated, future work should thus explore the sensitivity of SOC benefits via using an ensemble of PTFs. Moreover, measurements of soil hydraulic properties in combination with SOC, texture and bulk density in long term field trials investigating management alternatives affecting SOC would provide very useful evidence to help disentangle the effects of land use and management on the relationships between soil texture and hydraulic properties. By integrating management and also local climate information in PTFs, their uncertainties in predicting soil hydraulic properties in specific context could be reduced (Van Looy et al., 2017). Many historic records do not provide sufficient information on how certain measurements were performed, or when the samples were taken. Also, the timing of field sampling is likely to play a role here, as it is known that soil hydraulic properties vary in time and are influenced e.g. by precipitation regime or land use and management (Caplan et al., 2019; Lu et al., 2020).

In this study, we focused on transpiration reduction, which is likely to imply biomass reduction, but may not necessarily imply yield reduction – depending on the timing of water stress. Other studies have investigated impacts of CC on yields for grain maize in Switzerland (Holzkämper, 2020; Holzkämper et al., 2015a) and it was found that yield trends differ depending on the choice of varieties assumed to be planted. In our study here, we focus on drought impacts on crop transpiration alone. Subsequent yield formation will be affected by crop transpiration, but also by various other drivers (e.g. temperature & radiation limitations, timing of stresses, heat stress). In order to obtain a clearer view on the impacts of SOC increases on crop transpiration, we elected not to consider the multitude of such interactive effects in the presented study. In future work, it will be interesting to explore possibilities to further increase the benefits of SOC additions by combining that strategy with other adaptations of crop and soil management (e.g. earlier maturing varieties, cover cropping, mulching of soil to reduce evaporation). In this context, it will be advisable to also account for a dynamic development of phenology and thus leaf area index to account for possible interactions between crop growth and soil moisture conditions.

While our study focused solely on the impacts of SOC additions on soil water dynamics, SOC increases could have additional benefits for crop productivity and yield stability by feeding and supporting beneficial microbial communities in the soil (e.g. rhizobacteria, nitrogen-fixing bacteria, and mycorrhizal fungi), which increase the crops' ability to take up water and nutrients (Coban et al., 2022; Renwick et al., 2021; Kallenbach and Grandy, 2011). Such aspects could be addressed in future field experimental studies. Beyond that, future field- and model-based studies may also evaluate trade-offs or synergies of SOC promoting management strategies with regard to other soil-related ecosystem service indicators such as nitrate leaching, soil loss or runoff generation to provide insights regarding the possibilities to increase the sustainability of agricultural production overall (Bonfante et al., 2019). Alternative modelling approaches considering dynamic changes in soil hydraulic properties could also be applied in the future to investigate the influence of soil structural dynamics on the adaptation benefits of SOC accumulation (e.g. based on Meurer et al. (2020b), Meurer et al. (2020a)), as to our understanding, current models do not facilitate the representation of soil as a temporally variable medium.

7. Conclusions

Our study is the first to investigate the possibilities to reduce $Tred_{dry}$, an indicator of drought stress, in maize cultivated in the Swiss Central Plateau through increasing SOC in the top- and subsoil. Our simulations showed that $Tred_{dry}$ in maize is expected to increase with climate change in the Swiss Central Plateau region, by around 60-65 mm irrespective of SOC increase. Increasing SOC in a typical agricultural soil in Switzerland, however, is beneficial to reduce drought limitations in maize, showed by consistently positive average transpiration gains. These benefits are minimal if SOC is only increased in the top 25 cm, but become considerable if SOC is increased down to 65- or 135 cm depth. With a 2% addition of SOC down to 65cm depth, a considerable average transpiration gain of 40 mm can be reached. This scenario can be achievable considering management adaptations such as cover cropping or compost applications. It appears that a greater or deeper SOC addition would not return substantial extra benefits in terms of offsetting more crop drought stress rooting in the changing climate.

8. Author contribution

Conceptualization[1,3], Data curation[1], Formal analysis[1,3], Funding acquisition[3], Investigation[1,2,3], Methodology[1,3], Resources[3], Software[1], Visualization[1], Writing – original draft preparation[1,3], Writing – review & editing[1,2,3].

[1]MET; [2]AN; [3]AH

9. Competing interests

The authors declare that they have no conflict of interest.

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