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ORIGINAL ARTICLE

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Organic carbon controls water retention and plant available water in cultivated soils from South Greenland

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Abstract

The warming climate is rapidly changing the circumpolar region, presenting new opportunities and challenges for agricultural production in South Greenland. The warming climate is projected to increase the frequency of drought periods, but little is known about the soil–water retention (SWR) and the plant available water (PAW) of the agricultural soils in the region. This study aimed to measure the SWR and PAW of Greenlandic agricultural soils and evaluate the effect of organic carbon (OC) and clay (CL) content using pedotransfer functions based on OC and CL. The study included 464 South Greenlandic agricultural soil samples from 20 fields with a wide distribution in clay (0.016–0.184 kg kg^{-1}) and OC contents (0.006–0.254 kg kg^{-1}). Pedotransfer functions were successfully developed for estimating the gravimetric water content (w) at five soil–water potentials (−1500, −100, −30, −10, and −5 kPa) and PAW. The OC content was the primary variable governing the gravimetric water content at each soil–water potential, evidenced by R^2 values consistently above 0.80. The effect of OC on the gravimetric water content at −1500 kPa was close to the range reported in the literature, but OC effects were markedly higher between −100 and −5 kPa. Overall, this study highlights a substantial effect of OC on the PAW as a 1% increase in OC increased PAW by more than 4%, which is almost twice the value of a recent meta-study. Our study highlights the potentially dominating effects of organic matter on soil–water balance and availability in high-latitude agriculture.

Abbreviations: CL, clay; IG, Igaliku; OC, organic carbon; PAW, plant available water; PTF, pedotransfer function; QA, Qassiarsuk; RMSE, root mean square error; SI, South Igaliku; SWR, soil–water retention; SWRC, soil–water retention curve; UP, Upernaviarsuk; w, gravimetric water content.

1 | INTRODUCTION

Climate change is rapidly changing the Arctic regions, where the rate of warming has been twice the global average (Francis & Vavrus, 2012). As a consequence of the rapid warming, the climatic boundary for agricultural production will shift northward by up to 1200 km by 2100 (King et al., 2018). Rising temperatures will eventually change agricultural production in South Greenland, which presently is constrained by the cold climate (Caviezel et al., 2017; Westergaard-Nielsen et al., 2015). According to recent climate models by Christensen et al. (2016), the mean annual temperature in South Greenland will increase by 1.8–3.9˚C, thereby increasing the length of the growing season by 27%–50% by the end of the century. Thus, the climatic changes are projected to significantly increase future biomass production in the region (Westergaard-Nielsen et al., 2015). However, the success of agriculture is contingent on more than temperature, and drought periods are a frequent phenomenon in South Greenland (Caviezel et al., 2017). Unfortunately, climate projections indicate that drought periods and storms will become more frequent in South Greenland during this century (Christensen et al., 2016). Consequently, the future agricultural production will largely be dictated by irrigation and the inherent ability of the Greenlandic soil resource to store water, that is, their soil–water retention (SWR).

Knowledge of the SWR is integral to water management; it is necessary for planning irrigation and modeling plant growth, water flow, and solute transport (Saxton et al., 1986; Šimůnek et al., 2003). However, little is known about the SWR of the subarctic agricultural soils of South Greenland. The literature predominately consists of archaeological and geomorphological studies (e.g., Adderley & Simpson, 2006; Jakobsen, 1991; Massa et al., 2012; Schofield et al., 2010). The anticipation of a warmer climate has prompted a renewed interest in these soils, focusing on their nutrient availability (Caviezel et al., 2017), structural development (Pesch et al., 2021), gas diffusion characteristics (Weber et al., 2020), mechanical properties (Pesch et al., 2020), and soil–water repellency (Blaesbjerg et al., 2022; Weber et al., 2021). The soils are generally characterized by a relatively coarse particle size distribution, high organic carbon (OC) contents, and poor structural development (Jakobsen, 1991; Pesch et al., 2021; Weber et al., 2020). However, no studies have investigated the SWR of these subarctic soils. Caviezel et al. (2017) speculated that the Greenlandic soils would exhibit poor SWR and a low amount of plant available water based on their grain size distribution dominated by coarse particles and the, often, shallow soil depths.

Direct measurements of SWR are expensive, laborious, and time-consuming, which has led to the development of numerous pedotransfer functions (PTFs) to predict the SWR from basic soil properties, for example, particle size distribution and OC content (Jensen et al., 2015; Karup et al., 2017; Van Looy et al., 2017). The PTFs generally focus on predicting the water content at a specific matric potential or the parameters for continuous soil–water retention curves (Cornelis et al., 2001). However, the applicability of such PTFs is questionable for Greenlandic soils, as the OC content often is higher than the range supported by existing PTFs (Bagnall et al., 2022; Minasny & McBratney, 2018; Saxton & Rawls, 2006) and the fact that the performance of PTFs generally deteriorate when applied outside the geomorphological region which they were developed for (Van Looy et al., 2017). The clay and OC content have been identified as two of the principal parameters governing the SWR from saturation to oven-dry conditions (Jensen et al., 2015), but the quantitative effect of OC content on SWR and the plant available water (PAW) remains unclear and is strongly debated (Bagnall et al., 2022; Bauer & Black, 1992; Minasny & McBratney, 2018). In a recent meta-study, Minasny and McBratney (2018) evaluated the effect of OC content on the gravimetric water content (w) at key soil–water potentials as well as the gravimetric PAW. They did so by assessing the increase in gravimetric water content and PAW relative to the increase in OC content, that is, the constants of proportionality: $\Delta w/\Delta OC$ and $\Delta PAW/\Delta OC$. For a dataset consisting of 25 studies, Minasny and McBratney (2018) reported mean $\Delta w/\Delta OC$-values of 3.71, 1.36, and 2.13 for the gravimetric water content at field capacity (between −5 and −33 kPa), the gravimetric water content at the permanent wilting point (−1500 kPa; w_{-1500}), and the gravimetric PAW, respectively, indicating that the PAW increased by 2.13% for every 1% increase in OC content. Considering the highly organic nature of the Greenlandic soils, such a relationship would effectively result in OC dictating the SWR and PAW of these subarctic soils.

Core Ideas

- This is the first comprehensive study measuring the soil–water retention (SWR) of Greenlandic agricultural soils.
- The SWR and plant available water (PAW) were determined for 464 soils originating from 20 agricultural fields.
- Pedotransfer functions were developed to evaluate the effect of organic carbon (OC) and clay content.
- OC was the primary variable governing the SWR of these subarctic soils, especially at matric potentials ≥ −100 kPa.
- The impact of OC content on the SWR and PAW was high compared to the literature.

The primary aims of the present study were thus (i) to measure the SWR at five soil–water potentials ranging from −5 to −1500 kPa and determine the PAW of subarctic cultivated soils from Greenland and compare these results with the literature results from other geomorphological regions and (ii) to develop region-specific clay and OC-based pedotransfer functions to evaluate the relative influence of OC and clay content on the SWR and PAW of these subarctic agricultural soils.

2 | MATERIALS AND METHODS

2.1 | Study area

This study includes 464 soil samples from four agricultural areas in South Greenland: Qassiarsuk (QA, 61˚09′ N 45˚30′ W), Igaliku (IG, 61˚00′ N 45˚26′ W), South Igaliku (SI, 60˚53′ N 45˚16′ W), and Upernaviarsuk (UP, 60˚44′57.3″ N 45˚53′24.4″ W). The areas constitute a large part of the main agricultural region of South Greenland, where cultivated land is primarily used for grazing and fodder production (Westergaard-Nielsen et al., 2015). The four areas are distributed within Narsaq, Qaqortoq, and Vatnerverfi peninsulas and the two fjords, Tunulliarfik and Igalikup Kangerlua (Figure 1).

The study area has a long agricultural history dating back as early as 985 C.E. (Caviezel et al., 2017). Due to its cultural significance, the area has recently been appointed as a UNESCO World Heritage Area (*Kujataa*). The areas closest to the ice sheet are categorized as subcontinental, while the areas closer to the open ocean are oceanic (Jacobsen, 1987). The mean annual precipitation ranged from 615 to 858 mm (1961–1990), increasing from the inner parts (Narsarsuaq) to the outer parts of the fjords (Qaqortoq). For the same period, the mean annual temperatures were −3 to 4.8 and −2.9 to 4.0˚C at the two locations, respectively (Hanna & Cappelen, 2002). Prolonged periods of drought are a frequent phenomenon in the region, as the rainfall exhibits large inter-annual variability, and approximately half of the annual precipitation falls outside the growing season (Caviezel et al., 2017; Christensen et al., 2016; Hanna & Cappelen, 2002). Further, dry katabatic winds (Foehn winds), which generally occur six to seven times during the summer, can deplete the soil–water storage with their high evaporative demand of up to 16 mm d^{-1} (B. U. Hansen, 1991). The study area is generally devoid of permafrost (Daanen et al., 2011).

2.2 | Soil sampling and analysis

The soil samples were collected during sampling campaigns in August 2015, 2017, and 2018, as described by Weber et al. (2021), and the sampling followed the same procedures. In brief, 464 points were sampled across 20 fields in rectangular grids with 7.5-m by 7.5-m to 15-m by 15-m spacing. All 20 fields had a cropping history of perennial grass mixtures for pasture or winter fodder production. The grass mixtures consisted primarily of timothy (*Phleum pratense* L.), colonial bentgrass (*Agrostis tenuis* L.), Kentucky bluegrass (*Poa pratensis* L.), red fescue (*Festuca rubra* L.), and red clover (*Trifolium pratense* L.). The tillage operations, which typically involve disc harrowing the top 10–15 cm, are rarely performed in the region, and the majority of the fields had not been tilled for more than 5 years. At each sampling point, three 100 cm^3 undisturbed soil cores and approximately 2 kg of bulk soil were collected from the upper 5 cm of the A-horizon (5–15 cm soil depth, depending on the thickness of the turf layer). Prior to laboratory analyses, the bulk soil was air-dried and sieved to <2 mm, while the undisturbed soil cores were stored in a cooling chamber at 2˚C.

After organic matter removal by H_2O_2, the soil texture was measured on the bulk soil by a combination of wet-sieving and the pipette method (Gee & Or, 2002). None of the soils tested positive for calcium carbonate (verified by adding 10% HCl). Therefore, the OC could be set equal to the total carbon obtained from dry combustion using an ELTRA Helios C-Analyzer (ELTRA GmbH). The content of each textural fraction was calculated using an organic matter to OC ratio of 2, which has been suggested for Greenlandic soils by Weber et al. (2021, 2022).

The undisturbed soil cores were slowly saturated from below and sequentially drained to matric potentials of −5 and −10 kPa using a tension table with a hanging water column and further down to −30 and −100 kPa using Richards pressure plates. The soil cores were weighed between each draining step, and the gravimetric water content was determined as the difference in weight between the drained and oven-dried soil (105˚C for 24 h). While the gravimetric water contents at −100, −30, −10 and −5 kPa were determined for all 464 samples, the reference gravimetric water content at −1500 kPa was obtained for a subset of 141 soils taken from Weber et al. (2021), who used a WP4-T Dewpoint Potentiometer (Decagon Devices Inc.) to measure the SWR close to −1500 kPa. The PAW was defined as the gravimetric water content between −1500 and −30 kPa. The reference w_{-1500} for the remaining 323 soils was estimated using the best performing PTF for w_{-1500} (Table 3; Figure 5b; $w_{-1500} = 1.427 \times OC + 0.407 - 0.009$).

2.3 | Development of pedotransfer functions

Region-specific pedotransfer functions were developed to estimate the gravimetric water content at the five soil–water potentials (−1500, −100, −30, −10 and −5 kPa) and to assess the PAW. The PTFs consisted of simple or multiple linear regression models of the form: $w = a_n X_n + \ldots + b$, where

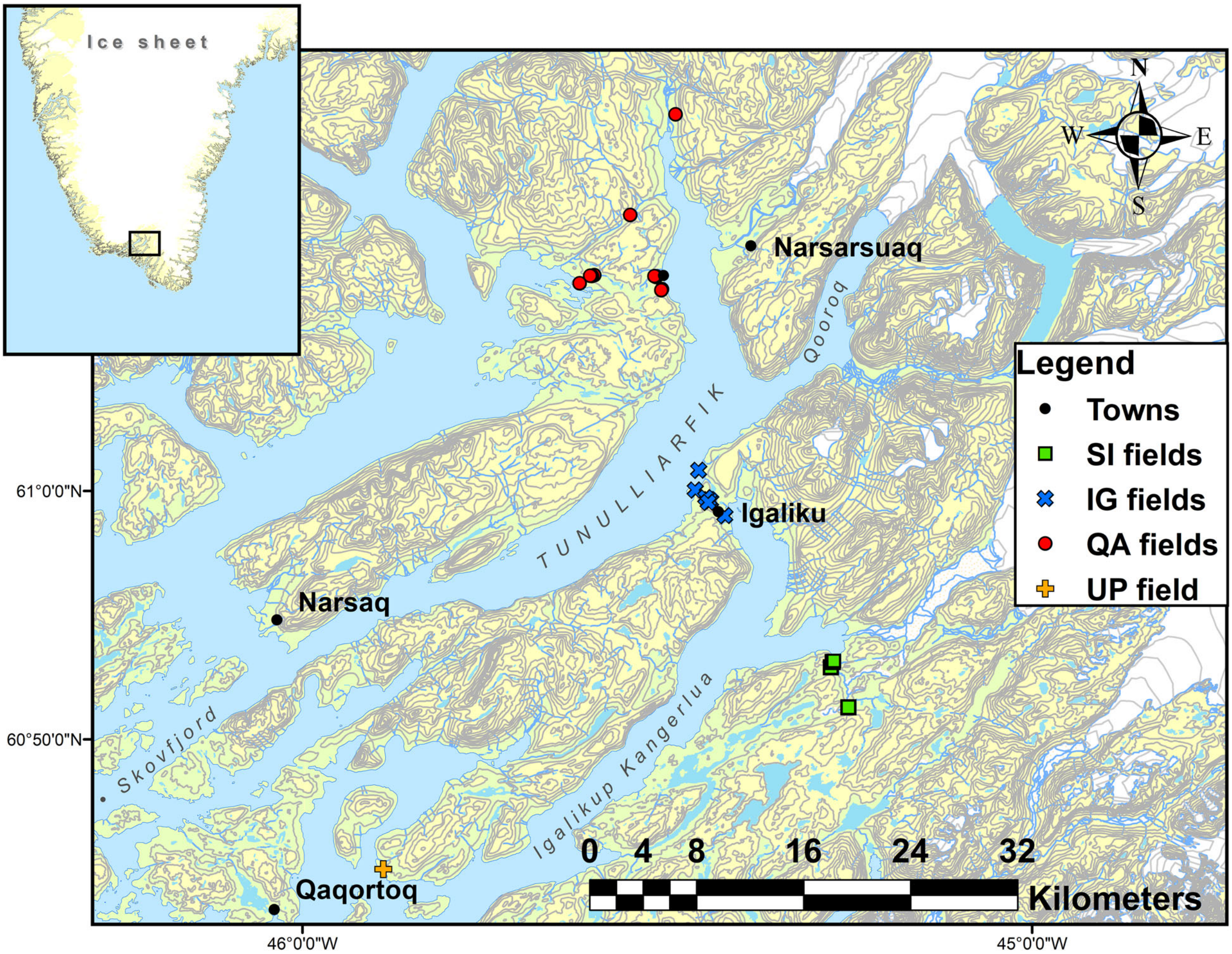

FIGURE 1 Map showing the wider study area and the location of the sampled fields with the red circle, blue cross, green square, and orange cross representing Qassiarsuk (QA), Igaliku (IG), South Igaliku (SI), and Coco (UP) areas, respectively

a_n is the regression coefficient for the predictor variable X_n, and b is a constant. For each of the five soil–water potentials and PAW, two PTFs were established with one and two predictor variables (OC and clay content), respectively. Predictor variables were considered significant at p-values below 0.05 (following a t-test). The overall performance of each PTF was evaluated by the root mean square error (RMSE) and the coefficient of determination adjusted for the number of predictors ($R^2{}_{adj}$). This approach also enabled a direct comparison of regression coefficients (e.g., Δw/ΔOC and ΔPAW/ΔOC) to previous studies, including the recent meta-study by Minasny and McBratney (2018).

3 | RESULTS AND DISCUSSION

3.1 | Basic soil properties and soil–water characteristics

The 464 soil samples included in this study occupied four USDA textural classes: loamy sand, sandy loam, loam, and silt loam (Soil Survey Staff, 1999). The regions QA and IG showed the largest variation, with samples representative of all four classes, while regions SI and UP represented the loamy sand and sandy loam classes (Table 1). The clay content ranged from 0.016 to 0.184 kg kg^{-1} with a mean value of 0.067 kg kg^{-1}; the OC content ranged from 0.006 to 0.254 kg kg^{-1} with a mean value of 0.052 kg kg^{-1}. The SI region exhibited the lowest average and the smallest variation in OC content compared to the QA, IG, and UP soils, which all showed comparable mean values slightly above the mean of the complete dataset (Table 1). The subset of soil samples used to determine the gravimetric water content at −1500 kPa (N = 141) showed a variation in texture representative of the larger data set with clay contents ranging between 0.016 and 0.172 kg kg^{-1} and OC contents between 0.009 and 0.226 kg kg^{-1} (Table S1).

Figure 2 shows the clay content as a function of OC content for the 464 investigated soils. For temperate soils, a clay:OC ratio (subsequently referred to as the Dexter n value) of 10 has been found to represent the approximate boundary where the clay minerals become saturated with

TABLE 1 Descriptive statistics ($N = 464$) for texture, organic carbon (OC) content, and gravimetric water content (w) from the four sampled subregions in South Greenland (QA, Qassiarsuk; IG, Igaliku; SI, Søndre Igaliku; UP, Upernaviarsuk)

Data	Statistic[a]	CL	Silt	Sand	OC	w_{-1500}[b]	w_{-100}	w_{-30}	w_{-10}	w_{-5}
		kg kg^{-1}								
QA ($N = 233$)	Min.	0.028	0.130	0.168	0.006	0.019	0.082	0.105	0.146	0.190
	Max.	0.172	0.592	0.769	0.254	0.464	1.421	1.739	2.123	2.247
	Mean	0.074	0.326	0.466	0.067	0.119	0.381	0.451	0.608	0.674
	Median	0.071	0.338	0.463	0.056	0.098	0.305	0.362	0.487	0.538
	Q1	0.056	0.289	0.413	0.040	0.076	0.242	0.289	0.398	0.439
	Q3	0.088	0.367	0.504	0.083	0.141	0.409	0.486	0.690	0.766
IG ($N = 123$)	Min.	0.028	0.187	0.232	0.014	0.048	0.140	0.161	0.191	0.202
	Max	0.184	0.472	0.644	0.185	0.279	1.136	1.304	1.642	1.793
	Mean	0.079	0.315	0.479	0.063	0.109	0.377	0.431	0.547	0.606
	Median	0.064	0.314	0.497	0.059	0.096	0.332	0.382	0.504	0.568
	Q1	0.046	0.300	0.444	0.050	0.084	0.283	0.327	0.447	0.498
	Q3	0.106	0.332	0.527	0.071	0.119	0.412	0.481	0.586	0.651
SI ($N = 88$)	Min.	0.016	0.160	0.558	0.009	0.016	0.070	0.104	0.264	0.298
	Max.	0.055	0.320	0.790	0.059	0.098	0.392	0.537	0.710	0.746
	Mean	0.032	0.232	0.690	0.023	0.039	0.162	0.219	0.376	0.440
	Median	0.031	0.232	0.698	0.021	0.035	0.147	0.191	0.346	0.412
	Q1	0.025	0.212	0.672	0.015	0.028	0.113	0.145	0.313	0.379
	Q3	0.037	0.247	0.717	0.028	0.047	0.199	0.269	0.406	0.487
UP ($N = 20$)	Min.	0.043	0.175	0.482	0.042	0.069	0.177	0.210	0.273	0.304
	Max.	0.086	0.253	0.689	0.121	0.180	0.628	0.720	0.955	1.047
	Mean	0.066	0.201	0.572	0.080	0.123	0.423	0.480	0.583	0.619
	Median	0.068	0.197	0.573	0.078	0.126	0.451	0.517	0.609	0.637
	Q1	0.059	0.186	0.534	0.071	0.103	0.314	0.366	0.435	0.465
	Q3	0.075	0.213	0.594	0.095	0.143	0.521	0.583	0.685	0.717
All ($N = 464$)	Min.	0.016	0.130	0.168	0.006	0.016	0.070	0.104	0.146	0.190
	Max.	0.184	0.592	0.790	0.254	0.464	1.421	1.739	2.123	2.247
	Mean	0.067	0.300	0.516	0.058	0.101	0.340	0.403	0.547	0.609
	Median	0.061	0.310	0.498	0.052	0.089	0.291	0.345	0.474	0.529
	Q1	0.044	0.242	0.440	0.029	0.064	0.207	0.257	0.369	0.417
	Q3	0.086	0.349	0.592	0.073	0.120	0.392	0.454	0.599	0.663

Note: Clay (CL): <2 µm, silt: 2–60 µm, sand: 60–2000 µm, and w measured at –1500, –100, –30, –10, and –5 kPa.

Abbreviations: Min., minimum; Max., maximum.

[a]Q1, first quartile of the data set; Q3, third quartile of the data set.

[b]w_{-1500} was measured for 141 samples and estimated using the OC+CL pedotransfer function (Table 3: $w_{-1500} = 1.427\ \mathrm{OC} + 0.407\ \mathrm{CL} - 0.009$) for the remaining 323 samples. The corresponding table for the 141 samples is shown in the Supporting Information (Table S1).

OC (de Jonge et al., 2009; Dexter et al., 2008). The Greenlandic soils thus exhibit exceedingly low Dexter n values, with only a few soils exhibiting a Dexter n above 10 and approximately half of the samples having a Dexter n below 1. The low Dexter n values indicated that most of the OC in the Greenlandic soils exists as non-complexed OC, which is freely available and unprotected by clay complexation (Dexter et al., 2008). The high content of non-complexed OC reflected the slow degradation and subsequent OC accumulation due to climatic conditions, low bioturbation, and the generally low amount of clay present in the Greenlandic soils.

The soil–water retention curves (SWRC) exhibited a considerable degree of between-field and within-field variation, which closely mirrored the distribution in OC content (Figure 3). Consequently, the largest within-field variation in SWRCs occurred in the QA-1 field (Figure 3a), exhibiting a range in OC content between 0.041 and 0.254 kg kg^{-1}. The majority of the SWRCs exhibited a log-linear behavior between −5 and −100 kPa, reflecting a broad pore size

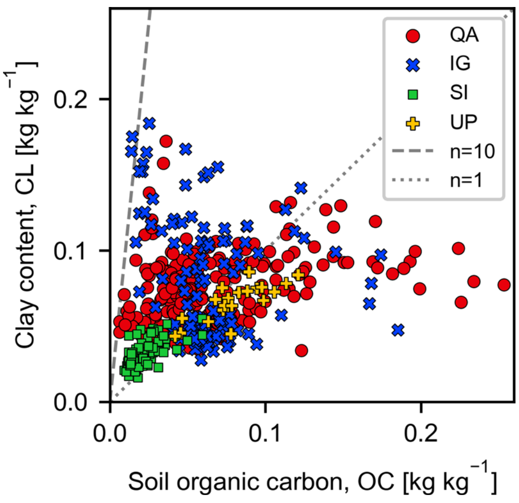

FIGURE 2 The clay (CL) content versus the organic carbon (OC) content with indicated Dexter n = 10 (dashed line) and 1 (dotted line). Dexter n was calculated as the CL:OC ratio

distribution between 3 and 60 µm. The coarse-grained soils from field QA-9 (Figure 3i), SI-1 (Figure 3p), SI-2 (Figure 3q), and SI-4 (Figure 3s) exhibited a relatively large drop in gravimetric water content between −5 and −30 kPa, which reflects a large proportion of pores within the diameter range 10–60 µm.

The visual representation of the SWRCs revealed that the investigated soils exhibited a marked variation of gravimetric water content across the soil–water potentials. The w_{-1500} ranged from 0.016 to 0.464 kg kg^{-1}, and the gravimetric water content at −5 kPa (w_{-5}) ranged from 0.190 to 2.247 kg kg^{-1} (Table 1; Figure S1). The SI region showed the lowest mean gravimetric water content at all soil–water potentials; in contrast, the QA region showed the largest variation, closely following the CL and OC content variations in both fields (Table 1).

3.2 | Water content at the permanent wilting point (−1500 kPa)

An investigation of soil–water retention data from 209 Danish soil samples, compiled by L. Hansen (1976), yielded a linear regression PTF for determining w_{-1500} using clay and OC content as predictors (R^2 = 0.69). The PTF was applied to the data from South Greenland (Figure 4a), and it predicted the w_{-1500} of the OC-rich Greenlandic soils well (R^2_{adj} = 0.867, RMSE = 0.027 kg kg^{-1}), despite the comparably low OC content of the Danish soils used for calibrating the PTF (0.01–0.02 kg kg^{-1}). An inspection of the regression coefficients of the PTF developed on the Danish soils revealed that the effect of OC on w_{-1500} was approximately twice as high as the effect of clay (Figure 4a).

Similarly, Jo (1990) developed a clay- and OC-based PTF for w_{-1500} on 144 South Korean paddy soils with an average OC content of 0.012 kg kg^{-1}. (Figure 4b). This model also performed well for the Greenlandic soils (R^2_{adj} = 0.865), although it generally overestimated w_{-1500}, which was reflected by the higher RMSE value (RMSE = 0.041 kg kg^{-1}). The OC coefficient of the PTF by Jo (1990) was 1.45, similar to the Danish PTF (1.458), while the clay coefficient (0.543) was markedly larger compared to the Danish PTF (0.365). In addition to the larger clay coefficient, the South Korean PTF also included a relatively large intercept (0.016 kg kg^{-1}), which together explained the overprediction of the Greenlandic w_{-1500}-values.

Two PTFs were developed on the Greenlandic soils to predict w_{-1500} (Figure 5). The single-variable OC-PTF resulted in an excellent fit (R^2_{adj} = 0.841 and RMSE = 0.024 kg kg^{-1}), which, together with the low intercept value (<0.01), indicates that the OC content governs the water content at the wilting point.

From visual inspection of Figure 5, the QA region, exhibiting the highest variation in texture, was better explained using the two-variable PTF. The OC coefficients were estimated at 1.547773 and 1.427 for the single- and two-variable PTFs. The coefficient for clay was 0.407, ranging between the ones estimated by the Danish and South Korean PTFs. In their meta-review, Minasny and McBratney (2018) compiled published data from 25 studies, which showed an average increase in water content at −1500 kPa with a 1% increase in OC content of Δw/ΔOC = 1.36 (Table 2).

The Δw/ΔOC reported by Minasny and McBratney (2018) is close to the one found by the single variable PTF with the Greenlandic samples as model soils. Bauer and Black (1992) studied the effect of OC on gravimetric water content of North American Great Plains soils representing three soil textural groups. The authors reported a Δw/ΔOC value of 1.74 for sandy soils, while medium and fine-textured soils exhibited a lower effect of OC and nonlinear behavior.

The relation between OC and w_{-1500} for the Greenlandic soils is similar to those found by other studies, despite the investigated soils having a higher OC content. The similar Δw/ΔOC points to a universal dry-region soil–water retention of OC across multiple climatic regions which was also noted for water vapor sorption isotherms of OC-dominated soil by Hermansen et al. (2021). Since the contribution of capillary water is close to negligible at −1500 kPa (Tuller & Or, 2005; Tuller et al., 1999), this behavior may be attributed to the fact that OC increases the specific surface area at a similar rate across soil types and climatic regions. However, these relationships may also be affected by confounding effects arising from, inter alia, variation in clay mineralogy and the degree of clay-OC complexation (Arthur et al., 2020; Resurreccion et al., 2011).

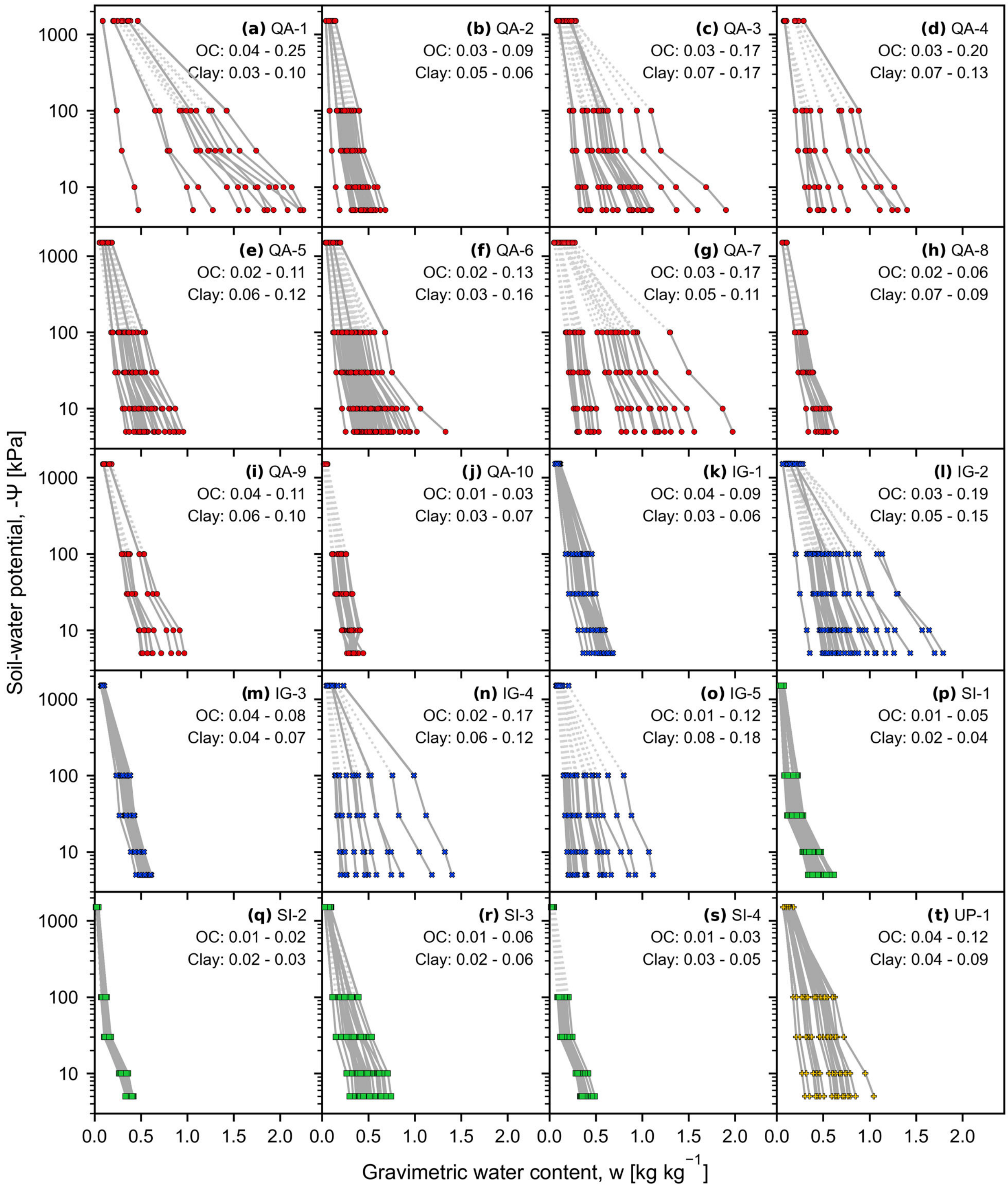

FIGURE 3 Overview of the measured soil–water retention curves for each of the 20 fields (a–t) in the areas of Qassiarsuk (QA), Igaliku (IG), South Igaliku (SI), and Upernaviarsuk (UP). The solid lines represent the measured part of the curves, while the dotted lines represent the 323 samples where w_{-1500} was estimated using the OC+CL pedotransfer function (Table 3: $w_{-1500} = 1.427\ \mathrm{OC} + 0.407\ \mathrm{CL} - 0.009$). The range in clay and organic carbon (OC) content for each field is given within each plot (both in kg kg^{-1})

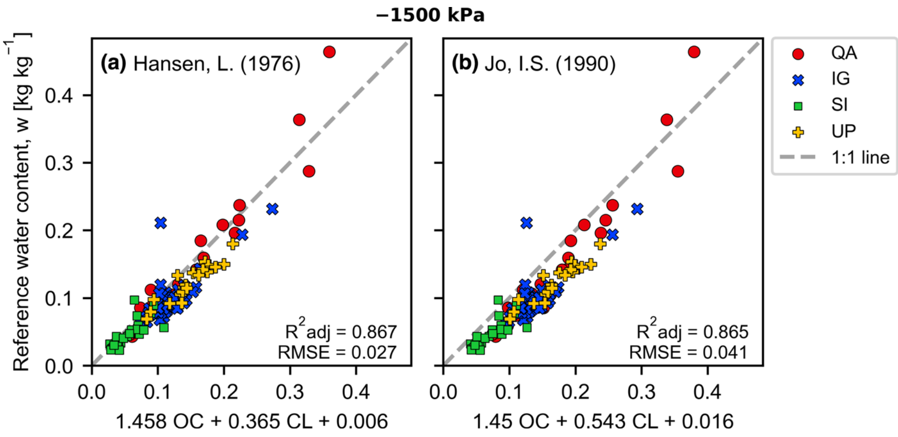

FIGURE 4 Reference water content at −1500 kPa (w_{-1500}) for the subset of 141 samples plotted against the w_{-1500} predicted using the existing pedotransfer functions (PTF) developed for (a) Danish soils ($N = 209$) by (Hansen, 1976), and for (b) South Korean paddy soils ($N = 144$) by Jo (1990). The equation for each PTF is given in the *x*-axis labels

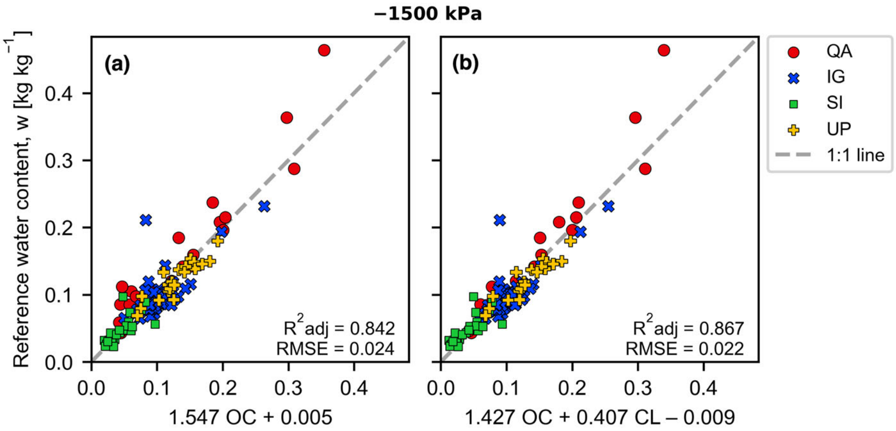

FIGURE 5 Reference water content at −1500 kPa (w_{-1500}) for the subset of 141 samples plotted against the w_{-1500} predicted by the new region-specific pedotransfer functions (PTF). (a) The single-variable pedotransfer function (PTF) with organic carbon (OC) content and (b) the two-variable PTF with OC and clay content (CL) as predictors

TABLE 2 Changes in water content (w) and plant available water (PAW) with changes in organic carbon content (OC) of the soils from South Greenland and literature expressed as their ratio (Δw/ΔOC and Δw/ΔPAW)

	Δw/ΔOC					ΔPAW/ΔOC
Study	−1500 kPa	−100 kPa	−30 kPa	−10 kPa	−5 kPa	$w_{-30} - w_{-1500}$
South Greenland (this study)	1.547	4.885	5.563	6.825	7.354	4.044
Minasny and McBratney (2018)	1.36	–	3.71[a]			2.13

[a] Δw/ΔOC gradient is a mean average found across 25 studies at field capacity between −33 and −5 kPa (Minasny & McBratney, 2018).

3.3 | Soil–water retention between −30 and −5 kPa

In addition to the PTFs established for the dry region, gravimetric water content was also estimated at −30, −10, and −5 kPa (w_{-30}, w_{-10}, and w_{-5}), with OC and CL as independent variables. The OC-based PTFs explained a large degree of the variation across the entire wet region, with R^2_{adj} ranging between 0.803 and 0.820 and RMSE values between 0.103 and 0.144 kg kg^{-1} (Table 3). Including clay content in the PTFs resulted in a relative increase in R^2_{adj} of 2.9% at −100 kPa, 1.6% at −30 kPa, 0.1% at −10 kPa, and 0.0% at −5 kPa, compared to the OC-based PTFs. Consequently, CL did not contribute significantly ($p > 0.05$) for the

TABLE 3 Pedotransfer functions for determination of soil–water content at five soil–water potentials: 1500, −100, −30, −10 and −5 kPa, and plant available water (PAW = $w_{-30} - w_{-1500}$) with organic carbon (OC) and clay content (CL) as independent variables

Predicted water contents	Soil–water potential	Pedotransfer functions	R^2_{adj}[a]	RMSE
	kPa			kg kg^{-1}
Semi-dry (N = 141)	−1500	1.547 OC + 0.005	0.841	0.024
		1.427 OC + 0.407 CL − 0.009	0.867	0.022
Semi-wet (N = 464)	−100	4.885 OC + 0.055	0.826	0.089
		4.608 OC + 1.108 CL − 0.003	0.850	0.082
	−30	5.563 OC + 0.078	0.820	0.103
		5.327 OC + 0.947 CL + 0.028	0.833	0.099
Wet (N = 464)	−10	6.825 OC + 0.148	0.813	0.129
		6.739 OC + 0.344[b] CL + 0.130	0.814	0.129
	−5	7.354 OC + 0.179	0.803	0.144
		7.329 OC + 0.098[b] CL + 0.174	0.803	0.144
PAW ($w_{-30} - w_{-1500}$)	–	2.044 OC + 0.065	0.729	0.098
		3.912 OC + 0.530 CL − 0.038	0.736	0.096
		4 OC	0.729	0.119

Abbreviation: RMSE, root mean square error.
[a]R^2_{adj}: coefficient of determination adjusted for the number of variables.
[b]Coefficient not significant ($p > 0.05$).

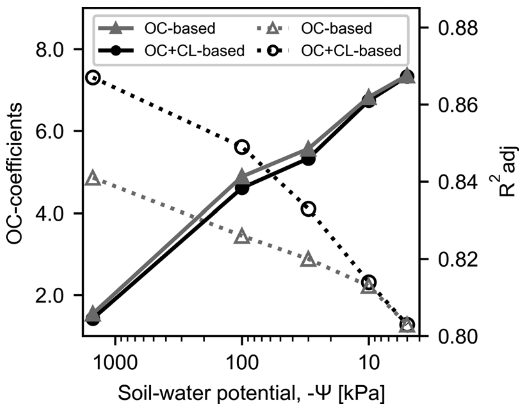

FIGURE 6 Organic carbon (OC)-coefficients (solid lines) and corresponding adjusted coefficient of determination (R^2_{adj}, dashed lines) for single variable OC-based and two-variable OC and clay content (OC+CL)-based pedotransfer functions for water contents at −1500, −100, −30, −10 and −5 kPa. Note that the x-axis is shown logarithmically

two-variable PTFs at −5 and −10 kPa; however, the PTFs were included in Table 3 to compare the parameter estimates across the different soil–water potentials. Finally, the best prediction models for gravimetric water content at −10 and −5 kPa were obtained by using OC as a single predictor. Table 3 presents the performance and parameter estimates for all six PTFs developed; a figure showing each regression is provided in the Supporting Information (Figure S2).

Figure 6 shows the OC-coefficients and the corresponding R^2_{adj}–values obtained from the single- and two-variable PTFs. It clearly illustrates the increasing OC-coefficients for all PTFs as the soil–water potential increases, demonstrating that the relationship between gravimetric water content and OC becomes less apparent when the proportion of capillary-held water increases (Tuller et al., 1999). This is likely the result of the confounding effects of soil structure and bulk density, which heavily affect the SWR close to water saturation (Rawls et al., 1991). Overall, weaker model performance at the high matric potentials agrees well with the study of Cornelis et al. (2001), which detected the highest errors at water contents near field capacity when evaluating the performance of a range of PTFs.

3.4 | PTFs for plant available water

Single- and two-variable PTFs were similarly established to determine the relationship between soil composition and PAW, that is, the gravimetric soil–water content held between −1500 and −30 kPa (Table 3). The CL contributed significantly to the two-variable PTF, which performed slightly better (R^2_{adj} = 0.736) than the single-variable PTF using OC as the only predictor (R^2_{adj} = 0.729). Both expressions generally underestimated PAW above ~0.5 kg kg^{-1}, and the coarse-grained SI soils deviated consistently from the 1:1 line (Figure S2). Considering the strong relationships found at −1500 kPa, the relatively low R^2_{adj} values can be ascribed to the variability at −30 kPa, which likely includes soil structure and bulk density effects (Rawls et al., 1991). Both PTFs demonstrated a linear relationship between PAW and OC for the Greenlandic soils close to PAW = 4 OC, resulting in an R^2_{adj} = 0.729.

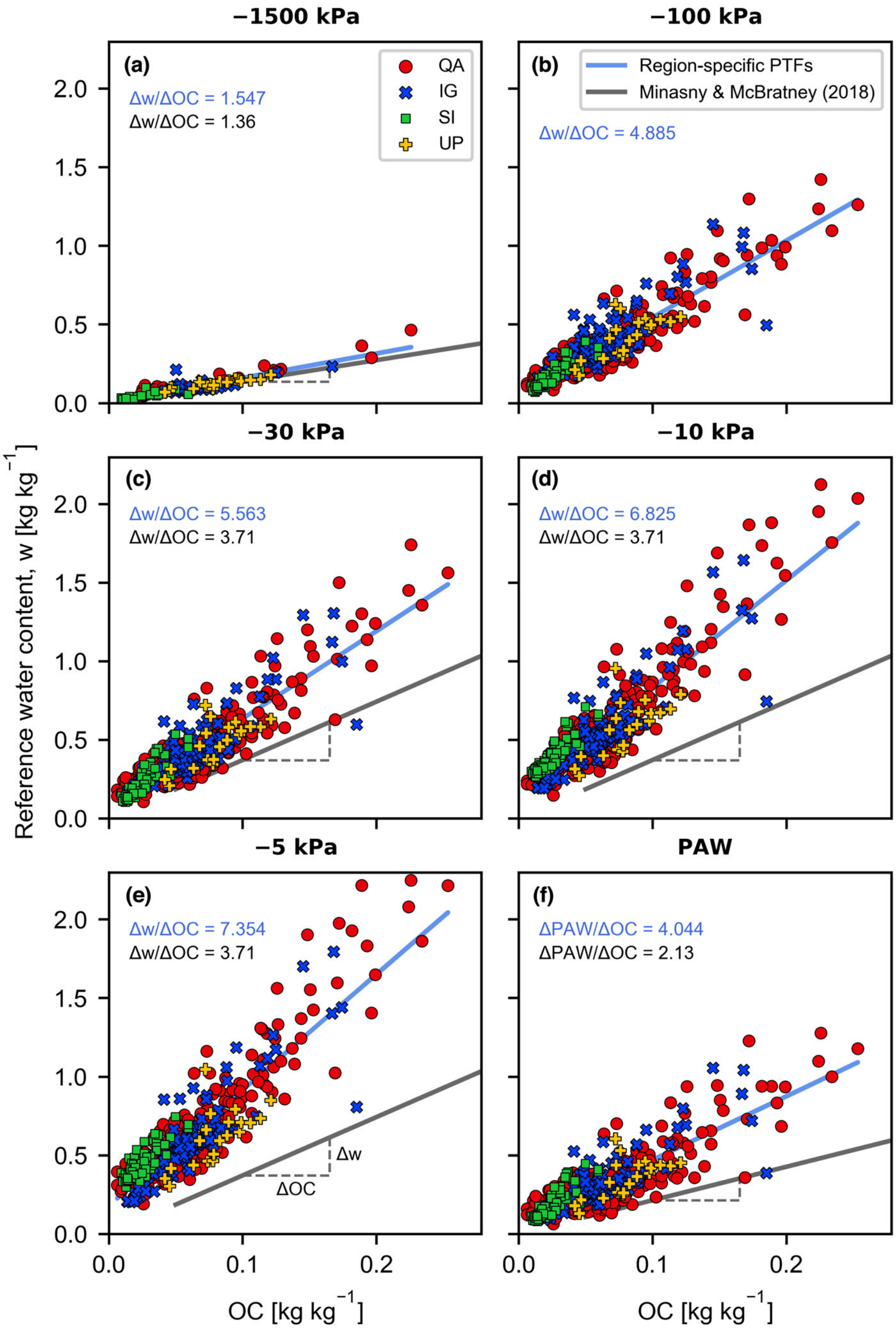

FIGURE 7 Relationships between soil–water content (w) at −1500, −100, −30, −10, −5 kPa, plant available water (PAW) and organic carbon (OC) content with Δw/ΔOC gradients of the region-specific pedotransfer functions (PTFs) (blue line). The gray line represents the Δw/ΔOC values from a meta-study by Minasny and McBratney (2018) at "wilting point" (−1500 kPa), "field capacity" (ranged from −33 to −5 kPa) and for PAW (difference between gravimetric water content at field capacity and wilting point)

3.5 | Effect of organic carbon on soil–water retention and plant available water

The water content increased with an increase in OC at all soil–water potentials and PAW, as shown in Figure 7. The Δw/ΔOC coefficients were 1.547, 4.885, 5.563, 6.825 and 7.364 at −1500, −100, −30, −10 and −5 kPa, respectively. The lowest gradient was found at −1500 kPa, the steepest at −5 kPa, and the Δw/ΔOC gradients corresponded to the OC regression coefficients were found in the single-variable PTFs given in Table 3. The largest drop was observed between −1500 and −100 kPa, reflecting the drainage of inter-aggregate pores (Resurreccion et al., 2008). Figure 7 also shows the Δw/ΔOC values reported by Minasny and McBratney (2018); they found a Δw/ΔOC of 3.71 for the field capacity (they included studies with gravimetric water content at −33, −10 and −5 kPa). The difference between the Δw/ΔOC of the Greenlandic soils and the average gradient found by Minasny and McBratney (2018) grew as the soil–water potential increased, demonstrating how the Greenlandic soils differed under increasingly wet conditions. The average Δw/ΔOC of gravimetric water content at field capacity of the Minasny and McBratney (2018) soils was closer to the Δw/ΔOC found for −1500 and −100 kPa in this study.

The Greenlandic soils are characterized by having a large content of particulate and non-complexed OC, which most likely results from the low decomposition rates due to the cold climate and short photosynthetic production period (Bradley-Cook et al., 2016). Recent studies by Pesch et al. (2021) and Weber et al. (2020) have highlighted that these subarctic soils exhibit a poorly developed soil structure and that OC heavily dictates their physical properties. Thus, a relative increase in OC content will likely increase the amount of particulate and non-complexed organic matter rather than developing hierarchical soil structures through organo-mineral complexation. Therefore, it was expected that the coefficients found in the region-specific PTFs around the field capacity would differ from those found in other studies conducted outside Greenland.

The study of Minasny and McBratney (2018) also reported the average increase in PAW with a 1% increase in OC content, ΔPAW/ΔOC = 2.13, which is visualized in the PAW versus OC plot in Figure 7f. The ΔPAW/ΔOC for the Greenlandic soils was approximately double the average ΔPAW/ΔOC reported by Minasny and McBratney (2018). Minasny and McBratney (2018) concluded that the OC had a limited effect on PAW, but the opposite is likely to be the case in Greenland, considering the above results. However, it should be noted that the Greenlandic soils were within the standard deviations reported across the 25 studies included in the review by Minasny and McBratney (2018). This is contrary to the early studies by, for example, Bauer and Black (1992), who argued that the addition of OC would cause an increase in water content across the entire SWRC, and therefore negligible net change in PAW. However, it is consistent with the findings of several newer studies that suggested that the addition of OC had the greatest effect in the wet range and therefore would increase PAW (Bagnall et al., 2022; Yost & Hartemink, 2019).

To summarize, the Δw/ΔOC coefficients at the wilting point were comparable to coefficients found in studies from outside Greenland. However, the coefficient found for the PAW differed greatly due to the larger Δw/ΔOC at −30 kPa. Consequently, the content of mesopores and micropores (<30 μm) increased at a higher rate with OC content than in temperate soils, which may be attributed to differences in the pore size distribution induced by the non-complexed OC, or a higher relative increase in total porosity with increasing OC contents compared to temperate soils.

The present study implies that the water-holding capacity and PAW of subarctic agricultural soils are contingent on their large pool of particulate and non-complexed organic matter, which is particularly concerning, considering that this type of organic matter exhibits the largest decrease with atmospheric warming (Rocci et al., 2021). In this type of climate, future management and adaptation strategies should thus seek to preserve the soils' OC pool to maintain their natural resilience against future drought periods, especially in areas where irrigation is not feasible or sustainable. Further, the pronounced OC effect on the SWR needs to be investigated for subarctic soils and incorporated into region-specific PTFs to support hydrological modeling in these hitherto sparsely studied soils.

4 | CONCLUSIONS

This study provided the first investigation into the soil–water retention of Greenlandic agricultural soils. From the 464 soil samples investigated in this study, we conclude that organic carbon content was the primary variable governing the soil–water retention of Greenlandic agricultural soils. While the gravimetric water content at the permanent wilting point (−1500 kPa) was governed by both clay and organic carbon content, the effect of clay became insignificant at soil–water potentials ≥−100 kPa. Model parameters representing the effect of clay and OC were well within the range reported in the literature for the permanent wilting point. However, model parameters representing the effect of OC on the water content close to the field capacity (−30 kPa) were twice as high as proposed by a recent meta-study by Minasny and McBratney (2018). Consequently, an increase in OC resulted in a relatively large increase in plant available water, which may be a result of the large content of non-complexed OC causing a higher content of mesopores and micropores (<30 μm) or a higher relative increase in total porosity, when compared to temperate soils.

AUTHOR CONTRIBUTIONS

Peter Lystbæk Weber: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Resources; Validation; Visualization; Writing – original draft; Writing – review and editing. **Natasha Hølk Blaesbjerg**: Conceptualization;, Data curation; Formal analysis; Investigation; Methodology; Software; Visualization; Writing – original draft; Writing – review and editing. **Per Møldrup**: Conceptualization; Formal analysis; Funding acquisition; Investigation; Methodology; Supervision; Writing – review and editing. **Charles Pesch**: Conceptualization; Formal analysis; Investigation; Methodology; Writing – review and editing. **Cecilie Hermansen**: Conceptualization; Formal analysis; Investigation; Methodology; Writing – review and editing. **Mogens Humlekrog Greve**: Conceptualization; Formal analysis; Funding acquisition; Investigation; Methodology; Resources; Supervision; Writing – review and editing. **Emmanuel Arthur**: Conceptualization; Formal analysis;

Investigation; Methodology; Writing – review and editing. **Lis de Jonge**: Conceptualization; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Supervision; Writing – review and editing.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

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