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RESEARCH ARTICLE

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Soil chemical changes in ancient irrigated fields of Udhruḥ, southern Jordan

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Abstract

Since ancient times, irrigation has been fundamental for achieving large agricultural yields, especially in the more arid areas of the world. An example of this practice is represented by the vast water infrastructures found near Udhruḥ (southern Jordan). These engineering works were constructed, maintained and restored from the Nabataean to early Islamic periods (first century BCE to eighth century CE). It still remains unknown why the ancient agricultural landscape of the region shifted towards an unproductive desert. In this study, we analysed the soil chemical and physical properties of an ancient irrigated field to assess whether ancient agricultural practices have altered soil properties that are still noticeable today, and might have contributed to the abandonment of the area. Soil samples were taken randomly from within an ancient qanat-irrigated agricultural field and from adjacent surfaces believed never to have been irrigated. Our results indicate that the effects of irrigation are still detectable today; electrical conductivity and total Na, B, Li and Sr in the soil of the ancient fields were significantly lower than those in the undisturbed control soils, which suggests leaching of soluble elements due to irrigation. Our results provide evidence of the mastery of ancient civilizations in their agricultural practices. Engineers and farmers apparently managed to conduct irrigation in the area of Udhruḥ for long periods of time without causing soil degradation.

KEYWORDS

irrigation agriculture, leaching, *qanat*, salinity, soil, Udhruḥ

1 | INTRODUCTION

Irrigation is pivotal to achieve significant crop yields in large parts of the world. About 40% of the world food output comes from irrigated areas, and it is estimated that this percentage will increase to 50% in the next decades (Schultz et al., 2005; WWAP, 2019). Also, in the past, societies in arid environments depended on irrigated agriculture (Driessen & Abudanah, 2018; Sandor et al., 2021). The highest consumption of water occurs in agriculture, and 70% of all global freshwater resources are used up annually; the vast majority is used

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The data that supports the findings of this study are available in the supplementary material of this article.

for irrigation purposes (WWAP, 2018). Arid regions—such as the Levant—face serious problems due to the scarcity of rainwater and its irregular distribution over the crop-growing seasons. An increasing demand for water and climatic changes will result in unsustainable depletion of groundwater stocks in the coming decades (Guermazi et al., 2019). Moreover, nearly all (approx. 90%) precipitation is lost in such regions through evaporation, surface runoff and seepage, and will thus not become available for agriculture or other uses (Rockström & Falkenmark, 2000).

Archaeological research clearly indicates that ancient societies dealt with similar challenges, whereby technologies were developed to reshape the environment to survive in arid areas that might seem inhospitable at first glance. In northern Jordan, communities made such adaptations to changing environmental and climatic conditions at the transition from the late Bronze to the early Iron Age (1300–1100 BCE) (Kaptijn & Ertsen, 2019). In the Udhruḥ region (southern Jordan), land-use systems and resource management, particularly elaborate water-harvesting schemes, were used to prevent precipitation loss for agricultural purposes from the Nabataean to the early Islamic periods (first century BCE to eighth century CE) (Driessen & Abudanah, 2018). The Udhruḥ Archaeological Project (Figure 1)—a joint-venture Dutch and Jordanian academic and expertise project—focuses on a better understanding of the diachronic development of the antique hydro-agricultural techniques that were used to cultivate this arid landscape and the societal conditions that contextualized them. In particular, this paper focuses on the effects of ancient-irrigated agriculture, by means of a *qanat* system (III in Figure 1), on soil properties.

The use of irrigation water may affect the soil quality in different ways. Irrigation water with high salt concentrations may increase soil salinity. Soil salinization decreases plant growth and contributes to desertification (Okur & Örçen, 2020). Together with the accumulation of salts, heavy metals from geogenic sources may accumulate as well (Arco-Lázaro et al., 2018). Soil salinization is a common problem in arid environments primarily because of the use of saline groundwater reservoirs for irrigation (Minhas et al., 2019) and the low availability of water, which leads to the accumulation of salts in the soil upper layers.

Soil science studies have been coupled with archaeology many times in the past, providing benefits to both disciplines (Goldberg et al., 2001; Holliday & Gartner, 2007). Signs of human activities have been detected also by conducting analyses on soil trace elements (Cook et al., 2006; Sulas et al., 2019). The long-term effects of agriculture on soils are, in general, difficult to study because of the lack of comparable 'undisturbed' locations (Wilson et al., 2008). However, the agricultural systems of Udhruḥ provide an opportunity for soil scientists: the agricultural fields seem to have been used for several centuries (Driessen & Abudanah, 2018). Soils located on

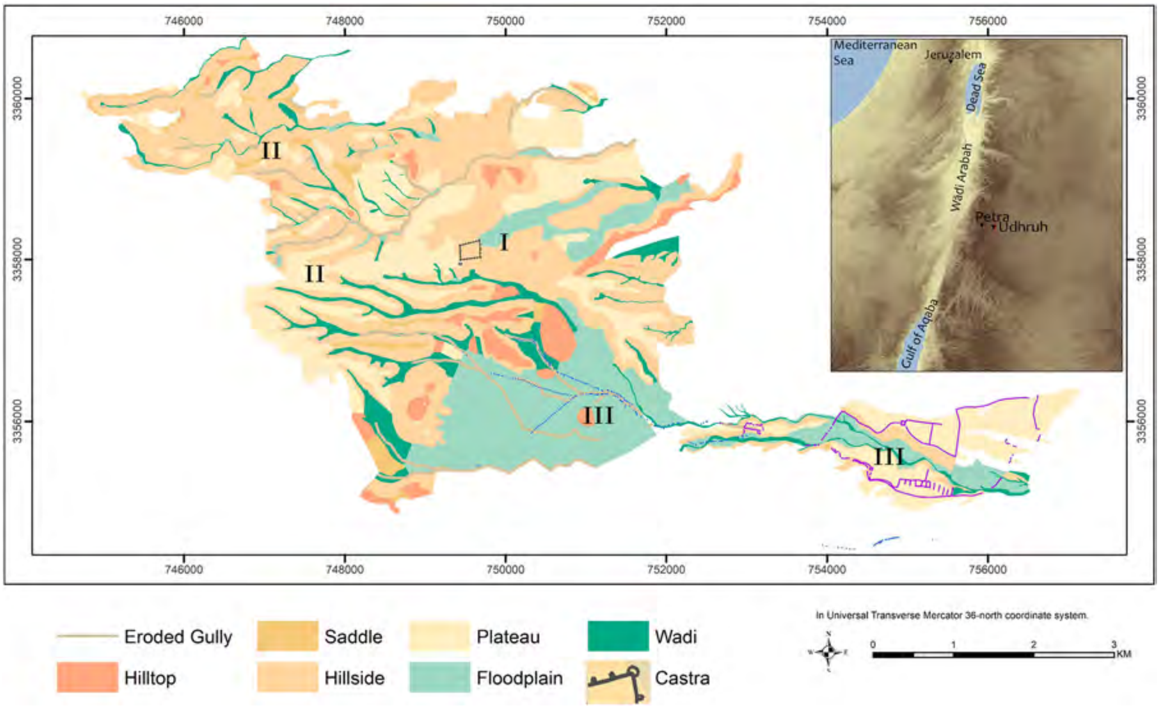

FIGURE 1 Topographic map of the research area of the Udhruh Archaeological Project (map by Roeland Emaus). Legend: I = irrigated compound gardens fed by perennial spring Udhruh (first century BCE to eighth century CE); II = Rainwater catchment and floodwater-harvesting systems, predominantly for the Nabataean (first century BCE to first century CE) and Byzantine periods (mid fourth to sixth century CE); III = Qanat system (from second to eighth century CE); parallelogram = Udhruh Roman fort and antique town; blue dots = *qanat* shafts; and purple lines = surface parts of the *qanat* system. Coordinates in the Universal Transverse Mercator 36-north coordinate system [Color figure can be viewed at wileyonlinelibrary.com]

comparable geomorphic surfaces adjacent to the irrigated fields provide an opportunity for comparative studies as they do not appear to have been irrigated. The soils of the ancient field are clearly demarcated by the remains of ancient walls. Second, the surface level of the surrounding control soils is quite uneven, especially when compared to the equally flattened surface of the fields laid out within the walled boundaries. The method and validity of comparing agricultural soils with natural soils to test for anthropogenic soil change are reviewed in Sandor and Homburg (2017).

The Udhruḥ Archaeological Project, a joint venture between Leiden University and Al Hussein Bin Talal University, started in 2011 with a field-survey programme and diverse GIS-related and subsurface-detection techniques to map the geomorphology and the wide variety of observed archaeological structures of the 48 km² research area (Figure 1). After 5 years of field campaigns, the Udhruḥ region revealed an actively exploited landscape reflecting investments of great effort and ingenuity in water management, agricultural intensification, trade services, communication and security networks (Driessen & Abudanah, 2018, 2019).

Through an interdisciplinary approach and the joint collaboration of archaeologists and soil scientists, this study aims to (1) assess the effects of ancient irrigation on soil properties and (2) assess whether ancient irrigation practices contributed to the abandonment of the agricultural area. We hypothesize that ancient irrigation deteriorated soil properties by increasing soil salinity, which contributed to the abandonment of the area.

1.1 | Archaeological and historical background

The current village of Udhruḥ, 12 km to the east of the Rose City of Petra, is dominated by and centred around the still standing remains of a Roman legionary fortress. Several Byzantine literary sources indicate that the military troops were replaced by civilian residents, and Udhruḥ became an important town, both under its local name and also known by the honorific title of Augustopolis (Fiema, 2002). The sixth-century Petra papyri provide very interesting socioeconomic and agricultural information on Petra and its hinterland and clearly indicate that Udhruḥ/Augustopolis became, next to Petra, a regional administrative centre where properties were registered and taxes were collected (Arjava et al., 2007). According to several Islamic sources, Udhruḥ remained a prosperous agricultural centre and the major town of the Umayyad province of Ash-Sharah in the eighth century CE (Fiema, 2002).

Three ancient hydro-agricultural systems can be distinguished in the Udhruḥ region, marked as I–III in Figure 1:

I. Udhruḥ hosted one of the most reliable perennial springs for the region: 'Ain Udhruḥ. This spring was a prime location factor also for the Nabataean settlement as the Roman legionary base, and it was also used to irrigate a patchwork of ancient and current compound gardens (Driessen & Abudanah, 2018, 2019). Below and next to the current network of water distribution channels, diversion structures, barriers and spillways, we encountered a system of many older stone walls and bunds. An abundance of ceramic finds from several periods leads us to surmise that this older system dates from the Nabataean period.
II. In the hilly area northwest of Udhruḥ, a combination of ancient rainwater-catchment and run-off water-harvesting techniques is observed, making it dependent on the short and sometimes turbulent rainy season. These water-harvesting schemes—consisting of walled terraces and conduit channels on the slopes of the hills, and dams and dikes in the wādī beds—were used to hold and direct run-off water. Similar harvesting and hillside conduit systems with both macro- and microcatchments have been found at other archaeological projects in the Petra region, and were dated by OSL (optically stimulated luminescence) and radiocarbon isotopy to the Nabataean period with possible use till the eighth century CE (Beckers et al., 2013). Our field surveys of the Udhruḥ run-off water-harvesting schemes and adjacent settlements resulted in ceramic evidence suggesting a Nabataean origin and a reuse for the Byzantine period (Driessen & Abudanah, 2018). Scientific dating for these systems in the direction towards Petra of intact mortar samples with charred twigs included still has to be accomplished, but has been carried out for several parts of the *qanat* system (III).
III. An impressive network of well-preserved ancient subterranean and surface-water conservation measures and connected irrigated fields—a *qanat*-system—was recorded on a large alluvial fan terrace (Wādī al-Fiqai) southeast of Udhruḥ. The Udhruḥ

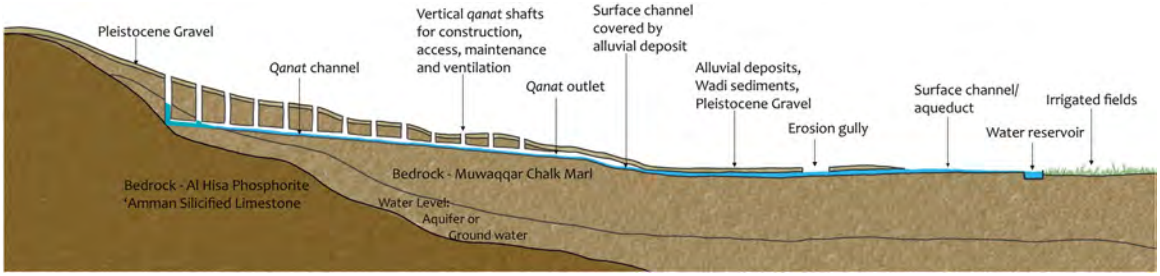

FIGURE 2 Schematic longitudinal cross-section of the Udhruḥ qanat (drawing by Kiki Driessen) [Color figure can be viewed at wileyonlinelibrary.com]

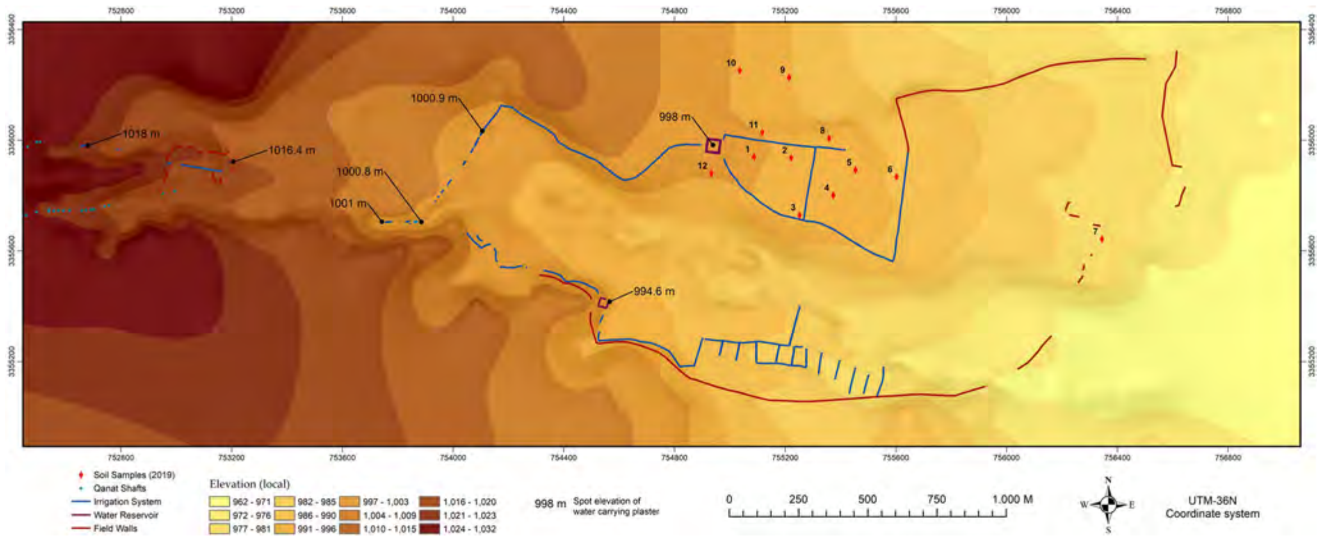

FIGURE 3 Surface part of the Udhruḥ qanat scheme in the Wadi el-Fiqai, including the locations of the sampling trenches (map by Roeland Emaus) [Color figure can be viewed at wileyonlinelibrary.com]

qanat (Figure 2 and 3) made use of the extraction of deep percolation water. The underground water transport by the *qanat* system also prevented water loss through evaporation. The system consists of subterranean and surface parts. The subterranean water system contains more than 200 vertical *qanat* shafts and horizontal water conduits. The surface part is made up of channels, aqueducts, distribution structures, large reservoirs and walled field systems with irrigation channels (Driessen & Abudanah, 2018). The preliminary reconstruction of this *qanat* system is based on aerial pictures (from the 1980s onwards), archaeological field survey observations, both at the surface and in an erosion gully, archaeological sondages and Ground Penetrating Radar surveying, but is still part of our ongoing archaeological research. Surface finds from the Wādī al-Fiqai flood plain yield a wide range of ages dating from the Nabataean to Islamic periods. OSL dating and ^{14}C analyses of charred twigs found in mortars from several parts of the surface part of the *qanat* point, however, to a possible construction in the Roman period with elaborate renovations in Byzantine and early Islamic times. It is quite possible that the rainwater-harvesting (II) and *qanat* systems (III) were contemporaneous in use. At present, it is not clear what crops were grown, as, unfortunately, samples from the fields do not contain macrobotanical remains, pollen or nonpollen palynomorphs. The Byzantine Petra papyri mention intensive cereal growing, viniculture and horticulture (Nasarat et al., 2012). The 2011–2015 Udhruḥ surveys resulted in dozens of quern stone fragments and a large olive press, which can be considered as evidence for the processing of wheat and olive oil.

The 8 km^2 qanat and related fields (system III) are the subject of the present interdisciplinary study. The soil samples were taken from an ancient field that was irrigated by this irrigation system, and from the surrounding control soils southeast of Udhruḥ, in June 2019 (30°18′28"N; 35°39′12"E). The field system is connected to a 50 × 50 m ancient water reservoir at the end of a system of *qanats*, channels and aqueducts.

1.2 | Environmental background

The ancient field is located in the eastern side of Jabal ash-Sharah highlands, with heights of 1500–1600 m. This area, at around 1100–1300 m above sea level, is situated at the so-called Eastern Highland Zone (Cordova, 2007). The Udhruḥ region lies at the boundary of two climate zones according to Köppen's classification: cool temperate Mediterranean climate (Csb) on the western side and cool semiarid climate (Bsk) at the eastern part of the research area. The research area receives 50–150 mm of annual precipitation—with higher rainfalls (150–200 mm) in the Jabal ash-Sharah than in the Eastern Highlands (50–100 mm)—which can be received through short intense downpours, predominantly in January and February (Kouki, 2012). The resulting flash floods can transform the *wādīs* into rapidly changing erosion gullies, as these currently lack systematic water regulation measures. The high infiltration capacity of the valley beds after short-lived cloudbursts, together with substantial evaporation as a result of solar intensity and strong western winds from the Wādi Arabah (Great Rift Valley), results in limited available run-off water (Bull & Kirkby, 2002). Palaeoclimatic studies show that the Iron Age–Byzantine periods were slightly more humid, but otherwise comparable to current conditions, followed by a drier phase in Islamic times (Besançon, 2010; Bruins et al., 2006; Finné et al., 2011; Gilbertson et al., 2007). The bedrock geology of the region is dominated by Cretaceous and Tertiary limestones. Soil samples for this study were taken in an area of Wādī al-Fiqai mapped as Pleistocene gravels overlying latest Cretaceous—Paleocene, limestone-dominated Muwaqqar $CaCO_3$ Marl Formation $CaCO_3$ (Kherfan, 1998). Soils in the area are predominantly Aridisols based on the US Department of Agriculture system showing weak development with high concentrations of gypsum or $CaCO_3$ (Al-Qudah, 2001). The natural vegetation in the area is scarce and predominated by dry steppe shrubs including *gaisoom* (*Achillea fragrantissima* (Forssk)), *athou* (*Anabasis syriaca* (Iljin)), *shieh* (*Artemisia herba-alba* (Asso)) and white weeping-broom (*Retama raetam* (Forssk)).

2 | MATERIALS AND METHODS

2.1 | Soil and water sampling

Six trenches were excavated within the field limits down to 60 cm depth, from which five samples were taken with increasing depth at each trench. These trenches were selected randomly from within the boundaries of ancient bordered fields (Figure 4). Excavated soil profiles showed accumulations of $CaCO_3$-like materials at depths below 50 cm (Figure 5). Another six trenches were excavated outside the bordered fields on an adjacent alluvial surface. These trenches were also selected randomly, but from the outside of the field. Sampling sites were located on flat surfaces away from erosion gullies. Five bulk sediment samples were collected at increasing depth within a vertical column in each trench. A summary of the trench GPS locations and $CaCO_3$ depth is presented in Table 1. Pebbles were removed when sampling the top layer. Samples were taken at approximately 10 cm depth intervals by scooping material into plastic

FIGURE 4 Aerial picture of the 50 × 50 m water reservoir (squared structure) and the connected walled field system in the Wadi el-Fiqai, taken from the West. Picture by David Kennedy, Aerial Photographic Archive for Archaeology in the Middle East [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Information of excavated trenches; see also Figure 3

Trench	Location/use	GPS: LON - X_UTM36N	GPS: LAT - Y_UTM36N	Appearance of $CaCO_3$ material (cm)
1	Ancient field	755088	3355941	55
2	Ancient field	755221	3355937	60
3	Ancient field	755252	3355731	60
4	Ancient field	755374	3355802	40
5	Ancient field	755454	3355894	35
6	Ancient field	755602	3355868	30
7	Control	756344	3355644	57
8	Control	755358	3356008	30
9	Control	755214	3356228	30
10	Control	755036	3356253	55
11	Control	755117	3356029	50
12	Control	754933	3355881	50

FIGURE 5 Current state of the ancient field and $CaCO_3$ accumulations (calcic horizon) in the soil profile. Numbers in the ruler indicate 10, 20, 30, 40 and 50 cm [Color figure can be viewed at wileyonlinelibrary.com]

bags. When large stones were found (larger than 5 cm diameter), these were removed from the sampling bags. Additionally, when possible, 100 cm^3 rings were placed in the soil to calculate a posteriori bulk density. No specific layers were observed in the soil profiles apart from the presence of a calcic horizon at variable depths (30–60 cm, Table 1) and a layer of compacted soil at the top that corresponds to a desert pavement formation. No differences in parent materials or soil classes were observed in the different excavated trenches.

Water samples were taken at the upper part of the qanat system from an active well used for agriculture (Figure 1). The water was pumped from a 155 m deep aquifer well below the antique qanat system.

2.2 | Bulk density

Soil bulk density samples were collected with 100 cm^3 rings (Eijkelkamp). Samples were sieved, and the rocks and pebbles were collected and weighed. The soil was then dried at 105°C to remove moisture and weighed again. The volume of the pebbles and rocks was accounted for by placing these solids in a 100 ml graduated measuring beaker and registering the increase in volume. Possible dissolution of $CaCO_3$ or other materials, if any, will be very low and therefore negligible. Finally, the bulk density of the soil was calculated by subtracting the rock weight and volume from the bulk soil weight and volume.

2.3 | Electrical conductivity (EC) and pH

EC and pH were measured in a suspension of 5.0 g of air-dried soil and 25 ml of distilled water (Buurman et al., 1996). After shaking for 30 min, EC was measured in a 5 ml subsample. The rest of the suspension was shaken for another 30 min, after which pH was measured.

2.4 | Cation exchange capacity (CEC)

CEC was measured on a selection of 20 samples. CEC is an indicator of the total amount of cations that the soil can retain. A total amount of 1.2 g of 5 mm sieved, air-dried soil was first equilibrated with Ba^{2+} to remove the indigenous exchangeable cations, and subsequently, Ba was exchanged with Mg^{2+} to quantify the total CEC (Gillman, 1979).

The two solutions, the first with the original cations replaced by Ba and the second with the Mg that remained in solution after the exchange with Ba in the soil, were then diluted. The first extract was diluted by a factor of 8 with 0.1 M $BaCl_2$ and the second by a factor of 10 with distilled water. These samples were then analysed by inductively coupled plasma atomic emission spectroscopy (ICP-AES). In the first extract Mg, Ca, Na, Fe, Al and K were measured and in the second extract, Mg was measured. The CEC was then calculated from the amount of Mg left in the second extract (Gillman, 1979).

2.5 | Available phosphorous

Available phosphorous (P) was assessed using the P-Olsen method (Olsen, 1954). 2.5 g of 5 mm sieved, air-dried soil was extracted for 30 min with 50 ml of 0.5 M sodium bicarbonate ($NaHCO_3$) at a pH of 8.5. After the extraction, the solution was filtered with a Whatman paper and collected in 10 ml polypropylene tubes. Then, an aliquot of 1.2 ml was taken from the solution and mixed with 4.8 ml of 0.15 M hydrochloric acid (HCl). The acidified solutions were then transferred to an ultrasonic bath to remove CO_2 bubbles. Finally, the PO_4 content of the solution was measured using a segmented flow analyser (SFA) (San++, Skalar).

2.6 | Organic carbon

For a selection of 30 samples, organic C was measured using the Kurmies method (Mebius, 1960). Five millimetre of sieved air-dried soil was milled into a powder. Oxidation of organic carbon is measured in a solution of sulphuric acid (H_2SO_4) with an excess of potassium dichromate ($K_2Cr_2O_7$) on a spectrophotometer (Thermo Spectronic Aquamate) at a wavelength of 585 nm. Organic C is quantified by determining the amount of Cr (III) that results from the reduction of Cr (VI) by the reacted amount of organic matter.

2.7 | Granulometry

Granulometry (particle size distribution) measurements were carried out by laser diffraction (Buurman et al., 1996). $CaCO_3$ present in the soil was removed by adding 1 M HCl until bubbling stopped. Organic matter was removed by adding 30 ml of hydrogen peroxide and placing the samples on a boiling bath. After cooling, demineralized water was added to a total volume of 250 ml and suspensions were allowed to settle for 24 h (or 48 h in case the supernatant was not clear yet). The supernatant was decanted and its EC was measured. Washing was completed when the EC of the supernatant was below 1000 µS/cm; otherwise, demineralized water was added again and the steps were repeated. Finally, the samples were ultrasonicated and dispersed using sodium polyphosphate and sodium carbonate, after which the size distribution of the dispersed soil particles was measured in a laser particle size analyser (Beckman Coulter LS230).

2.8 | Multitrace element analysis

A semiquantitative analysis was carried out on an HR-ICP-MS (Element2, Thermo Fisher) to identify elements in the soil samples. With a semiquantitative analysis, the ICP-MS was calibrated for the sensitivity of selected isotopes over the entire mass range using a standard with known concentrations for these isotopes/elements (see Table S1). After calibration, these isotopes plus isotopes from other elements that could be of interest for this study were measured on the ICP-MS. The concentrations from the directly calibrated isotopes/elements were calculated directly. The concentrations of elements that were not in the calibration standard were calculated using the known relative sensitivity for all masses on the ICP-MS. To limit interferences as much as possible, this measurement was carried out in high resolution mode (HR).

A selection of 30 soil samples from the two sampling locations was used for this analysis. The 0.43 M HNO_3 extraction method was used for this purpose to target the geochemically reactive element concentrations in the soil samples (e.g., possibly added by irrigation water) rather than elements occluded in primary soil minerals (Groenenberg et al., 2017). Three grams of air-dried 5 mm sieved soil was shaken together with 30 ml of 0.43 M HNO_3 for 4 h. Additionally, 3 ml of 5 M HNO_3 was added to dissolve all the $CaCO_3$ present. After shaking, samples were ultracentrifuged for 10 min at 3000 rpm. Then, the supernatant was filtered with a 0.45 µm carbon-free filter. Samples were then diluted 20 times to minimize the effect of the extractant (HNO_3) matrix on the ICP-MS measurement. To use the most sensitive resolution that is able to separate all the interferences from the intended isotope, the measurements were performed on high (HR), medium (MR) or low resolution (LR) (Table S1).

Additionally, the amount of trace elements in the water samples was quantified (Table S2). This was done for an estimation of the current chemical composition of the area's groundwater.

2.9 | Statistical analysis

All statistical analyses and graphs were performed using the software IBM SPSS version 25. Statistical differences among groups were calculated using Kruskal–Wallis one-way analysis of variance. The use of a nonparametric test was needed since some factors did not meet the parametric test assumptions such as normality or homoscedasticity. Effects were qualified as significant when the *p*-value was lower than 0.05; otherwise, the effects were considered nonsignificant. Variables were correlated by conducting a Spearman's correlation test (nonparametric).

3 | RESULTS

3.1 | Soil chemical and physical parameters

Soil pH was found to be alkaline (pH > 8) both outside and inside the field (Figure 6). The values of pH were higher in samples taken inside the field ($p < 0.001$). In contrast, the values of EC and Na were significantly higher in the samples taken outside the field.

Bulk density, P content and CEC showed differences only at certain depths (Figure 6). Clay, Ca and Mg contents showed no statistical differences between the samples taken inside and outside the field. Note that the values of Ca cations are higher than those of the CEC values. This can be attributed to the dissolution of Ca cations from $CaCO_3$ materials such as calcite during the cation removal step (Dohrmann & Kaufhold, 2009). Likewise, the high Na contents, especially in the control soils, may be due to the presence of free Na salts.

No differences were found for sand and silt particle size fractions (Table S5), indicating the similarity of the parent material at the sampling locations.

Finally, EC was positively correlated with Na and Mg and negatively correlated with bulk density, CEC, pH and P (Table S4).

3.2 | Multitrace element analysis

The trace metal analysis showed no signs of trace element enrichment in the ancient field. In contrast, Li, B and Sr were found to be depleted in the ancient irrigated fields (Figure 7). Of these trace metals, Sr was relatively abundant and was positively correlated with soil depth ($p = 0.043$, Spearman's $\rho = 0.37$). B, Li and Sr were also correlated with EC along the soil profile (Table S4). The concentrations of trace elements that were well above the detection limit are provided in Table S3.

4 | DISCUSSION

4.1 | Evidence of agriculture and irrigation effects

We found strong evidence of elemental leaching in the samples taken inside the ancient agricultural field (Figure 6). One of the most straightforward differences in soil properties inside and outside the field concerns the EC. EC was found to be orders of magnitude higher in the samples taken outside the field, and is an indirect measure of the salt concentration in the soil. In fact, the levels of Na were also more than 10 times higher in the samples taken outside the field (Figure 6), well correlating with the EC values (Table S4). In the presence of high contents of Ca or gypsum, Na can be easily leached from soils with irrigation (Gharaibeh et al., 2009). Divalent Ca ions can effectively replace monovalent Na ions from cation exchange sites on soil particles (Gharaibeh et al., 2009). Irrigation water, especially if it is not saline, has the potential of leaching nutrients and salts from the soil (Luedeling et al., 2005; Zeng et al., 2014). The analysis of the water samples collected in this study showed that the water that was most likely delivered to the fields through the *qanat* system had a low EC, thus indicating a low salt concentration (Table S2), making it feasible that the irrigation led to the observed depletion of soluble elements from the former agricultural soils. This is opposite of what we initially expected, since irrigation, especially in arid areas, often leads to soil salinization.

By looking at the trace elements in the soil, we also find evidence of irrigation (Figure 7). Trace element studies have been performed in the past in archaeological contexts to relate them to specific human practices (Cook et al., 2006). We found that Li, B and Sr were depleted in the samples taken inside the field. B, Li and, to a lesser extent, Sr are considered mobile elements (Frohne et al., 2015; Robinson et al., 2018;

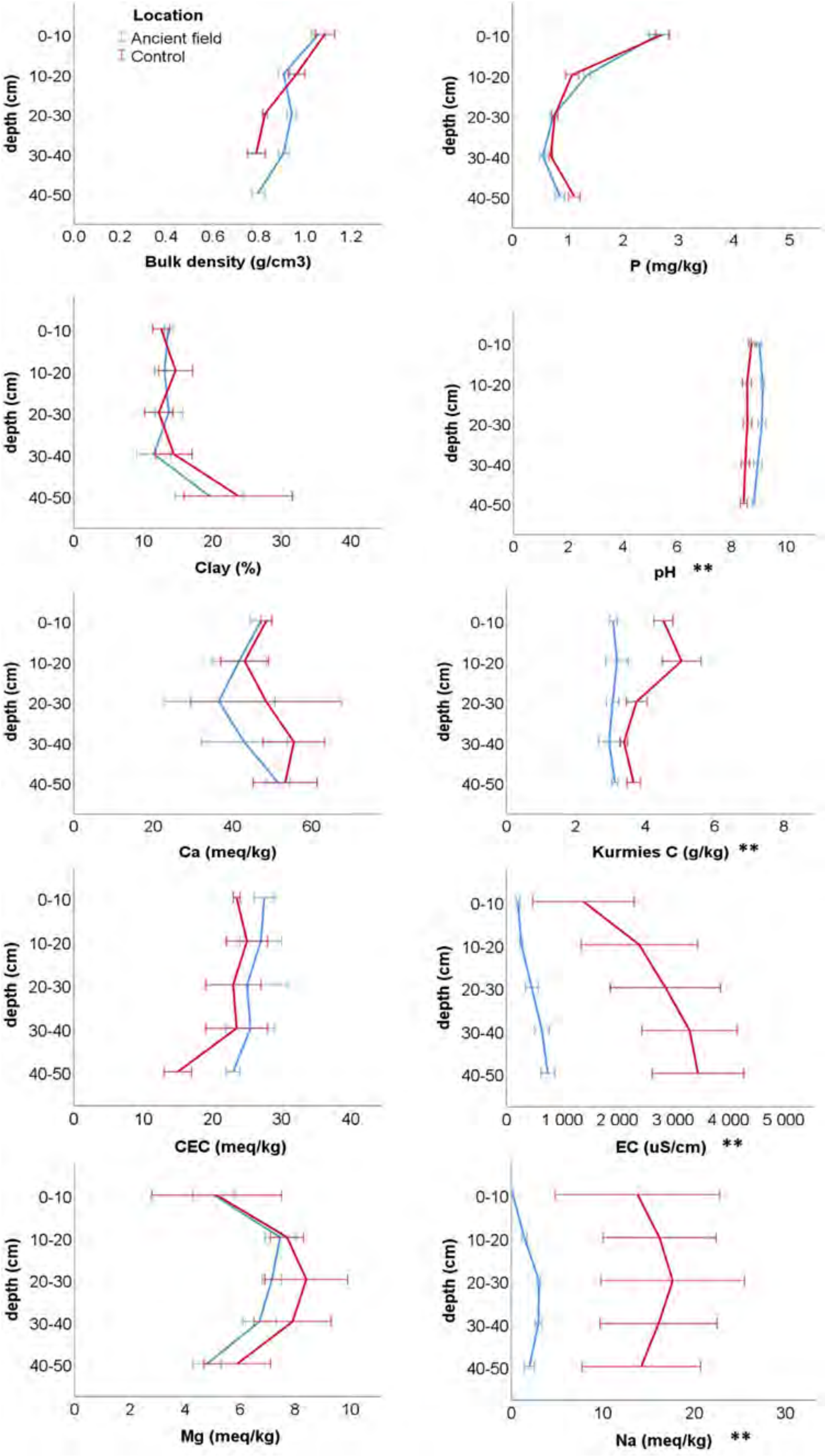

FIGURE 6 Soil chemical and physical parameters analysed across the complete soil profile. Error bars indicate the standard error. **Kruskal–Wallis test significance <0.001 [Color figure can be viewed at wileyonlinelibrary.com]

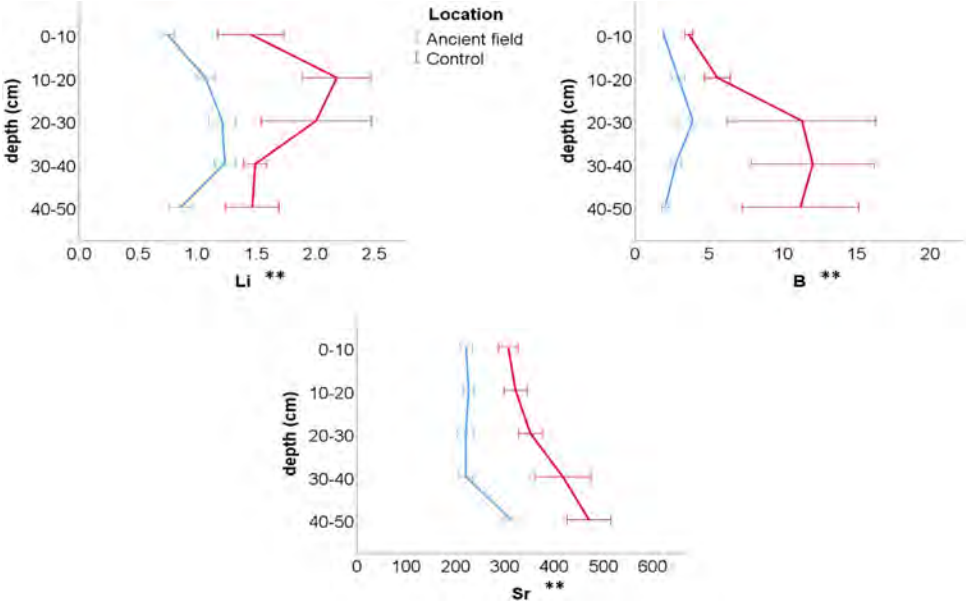

FIGURE 7 Trace metal concentrations along the soil profile. Concentrations are in mg/kg. Error bars indicate the standard error. **Kruskal–Wallis test significance <0.001 [Color figure can be viewed at wileyonlinelibrary.com]

Saleem et al., 2011). Interestingly, these three trace elements were found in relatively high abundance in the water samples, showing their relatively high solubility in the soils of Udhruḥ (Table S2). Therefore, we consider that the use of irrigation water could have leached these mobile elements from the ancient field, in the same way as other salts, as measured by the differences in EC. In fact, Li, B and Sr were also positively correlated with EC (Table S4).

Soil pH inside the irrigated field was found to be significantly higher compared to the control soils (Figure 6). These results may seem contradictory with the higher Na^+ concentrations found in the soils outside the field. Higher sodium content is commonly associated with increased soil pH. Yet, the leaching of hydrated salts could have also resulted in the depletion of sulphates within the irrigated field. Sulphates tend to acidify soils (Yang et al., 2007; Zhao et al., 2017); this effect may have diminished due to leaching, which may result in relatively higher soil pH values in the irrigated field. Another explanation could be the higher organic matter content in the control soils. Decomposition of this higher C content causes higher CO_2 concentrations in the soil, which, after dissolution, may cause lower soil pH ($CO_2 + H_2O \leftrightarrow HCO_3^- + H^+$).

Other factors that could explain element depletion inside the irrigated fields include plant uptake or tillage. Depleted elements inside the field may have been taken up by crops. In fact, elements such as Li, B and Sr have been reported to be bioavailable under certain chemical conditions (Ehlken & Kirchner, 2002; Robinson et al., 2018; Shah et al., 2017). For instance, the release of organic acids by ancient crops might have led to enhanced availabilities of trace metals (Antoniadis et al., 2017). These potentially higher amounts of organic acids could also explain the lower values of Kurmies OC (Figure 6). Yet, these differences on Kurmies OC were very small. Lastly, irrigation could have also changed soil microbial communities, which could have led to a depletion of OC contents (Qi et al., 2021).

4.2 | Ancient irrigation management

Our results reveal the mastery of ancient civilizations in their agricultural practices. Engineers and farmers managed to conduct irrigation in the area of Udhruḥ for long periods of time without causing evident soil degradation. It is common that, in semiarid or arid regions, irrigation leads to soil salinization (Elgabaly, 1977; Minhas et al., 2019; Tal, 2016). This was not the case at Udhruḥ; soil samples taken inside the irrigated field showed consistently lower rather than higher amounts of salts compared to the control soils (Figures 5 and 6).

Ancient farming communities most likely used efficient irrigation practices in combination with the use of large volumes of high-quality irrigation water that allowed salts to percolate (Luedeling et al., 2005; Zeng et al., 2014). Negative effects of irrigation thus do not seem to be the reason behind the abandonment of the area. Nevertheless, the current fertility status of the soil such as very low P contents, low organic matter, very high pH and high Na contents would have posed a challenge to ancient farming communities. How these communities managed to deal with those challenges remains unsolved. The cause of the abandonment of the area as an agricultural hub must thus be studied further by a multidisciplinary approach.

5 | CONCLUSION

In this study, we have presented evidence for the long-lasting effects of human agricultural activities, in this case specifically irrigation, on soil properties. Salts, as measured by EC, Na and mobile trace elements (B, Li and Sr), were leached from the soils of the ancient agricultural field. It appears that the irrigation system at Udhruḥ did not have negative impacts on soil properties, revealing the sustainability of the ancient agricultural methods used. This contrasts with current irrigation systems, which often lead to soil salinization in arid areas. If soil salinity was not the problem, why was agricultural production then discontinued? More insight into the antique agricultural system is thus needed to unravel the reasons behind abandonment of the sophisticated ancient agricultural infrastructure at Udhruḥ.

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