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Characterization of soil structure in Neuras, a Namibian desert-vineyard

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Abstract

Soil plays an important role in the context of vine growth and wine production; particularly soil structure which governs plant water uptake. Therefore, soil physical and hydrological properties were studied at Neuras vineyard, located near the Namib Desert. Water is scarce in this environment and wine production is limited to few vineyards in Namibia, overall. Managed plots and unmanaged nearby sites were investigated using field and laboratory methods. Viticultural techniques were noted and management related aspects were gathered in an interview. Datasets from two sampling trips in 2014 and 2016 were generated. In 2014, older vineyard soils displayed different properties than unmanaged soils or a younger vineyard, showing lower bulk densities and higher total porosities, with increased organic carbon and nitrogen contents. In 2016, the unmanaged reference plot differed from managed plots mainly in terms of lower electrical conductivity and higher cation exchange capacity. In managed soils contents of Smectites and Vermiculites were higher, while those of Chlorites and Illites were lower. Soil water retention properties were also altered, in line with structural changes indicated by bulk density and total porosity. These differences were more pronounced in vineyards of different ages than in those with even ages and indicate overall very different soil and soil structural conditions for the older versus the younger vineyards affecting vine growth.

Zusammenfassung

Der Boden spielt eine wichtige Rolle im Kontext des Rebenwachstums und der Weinproduktion; insbesondere die Bodenstruktur, die die Aufnahme von Wasser durch Pflanzen regelt. Daher wurden bodenphysikalische und hydrologische Eigenschaften im Weingut Neuras, in der Nähe der Namib-Wüste, untersucht. In dieser Umgebung ist das Wasser knapp und die Weinproduktion ist insgesamt auf wenige Weingüter in Namibia beschränkt. Bewirtschaftete Flächen und nicht bewirtschaftete, nahegelegene Flächen wurden mit Feld- und Labormethoden untersucht. Weinbautechniken wurden notiert und Managementaspekte in einem Interview gesammelt. Es wurden Datensätze aus zwei Geländekampagnen in den Jahren 2014 und 2016 generiert. Im Jahr 2014 zeigten ältere Weingutsböden andere Eigenschaften als nicht bewirtschaftete Böden oder als jüngere Weingutsböden und sie zeigten geringere Lagerungsdichten und höhere Gesamtporositäten mit erhöhten organischen Kohlen-

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stoff- und Stickstoffgehalten. Im Jahr 2016 unterschied sich die nicht bewirtschaftete von den bewirtschafteten Flächen hauptsächlich in Bezug auf niedrigere elektrische Leitfähigkeit und höhere Kationenaustauschkapazität. In bewirtschafteten Böden waren die Gehalte an Smektiten und Vermiculiten größer, während die an Chloriten und Illiten kleiner waren. Die Bodenwasser-Retentionseigenschaften wurden ebenfalls entsprechend der strukturellen Veränderungen, die durch die Lagerungsdichten und die Gesamtporosität angezeigt werden, verändert. Diese Unterschiede waren bei Weingutsböden unterschiedlichen Alters stärker ausgeprägt als bei Böden gleichen Alters. Sie weisen auf insgesamt sehr unterschiedliche Boden- und Bodenstrukturbedingungen für die älteren und jüngeren bestockten Rebflächen hin, die das Weinwachstum beeinflussen.

Keywords soil physical properties, soil moisture, soil structure, soil management

1. Introduction

Namibia is the driest country in southern Africa (*Jacobson* and *Jacobson* 2013) and droughts are normal (*Jacobson* et al. 1995). At the base of the escarpment just on the edge of the Namib Desert average annual precipitation is ca. 100 mm, westwards towards the coast it goes down to zero (*Jacobson* et al. 1995). Rainfall takes place from October to May, but mainly between January and April (*Jacobson* and *Jacobson* 2013). Mean pan evaporation rate in the Central Namib is ca. 3150 mm/y (*Jacobson* and *Jacobson* 2013) and ca. 3000 mm/y in the western catchments (*Jacobson* et al. 1995).

Land-use in the catchments of ephemeral rivers is focused on agriculture and tourism, which are two key factors of the Namibian economy with some areas being proclaimed for conservation (*Jacobson* and *Jacobson* 2013). The headwaters of Tsauchab River are private farmland (*Jacobson* et al. 1995), its lower reaches are located within the Namib-Naukluft National Park. The endorheic basin of Tsauchab River, Sossusvlei, along with the nearby Sesriem Canyon are popular tourist destinations; many farms in the area are focusing on tourism. In these arid ecosystems livestock farms are common, irrigated agriculture is limited to areas with access to springs or groundwater along the rivers. However, high evaporation rates as well as poor quality of water and soil pose problems and may lead to salinization (*Jacobson* et al. 1995).

Grapevines are one of the world's most economically important crops (*Kool* et al. 2016), but climatic conditions put restrictions on vine growth. The polar limits, for example, were discussed on the examples of Germany (50°N) and New Zealand (45°S) (*Endlicher* and *Fitzharris* 1995). But grape growing boundaries are not only pushed poleward using core cold resistant varieties, with irrigation they enter arid steppe and hot desert climates (*Dougherty* 2012). However, there are very few examples of famous wine-growing areas developing in inhospitable and remote areas, far from centers of consumption (*van Leeuwen* and *Seguin* 2006). More and more vineyards though are established in arid regions such as in Mendoza, Argentina, with 28.9 °C mean January temperature and 245 mm mean annual precipitation (*Martínez* et al. 2018), near Tenger Desert, China, with 8 °C and 164 mm mean annual temperature and precipitation, respectively (e.g. *Zhang* et al. 2008), and even in the Negev highlands, Israel, with high temperatures and < 100 mm/y in precipitation (e.g. *Kool* et al. 2016).

'Terroir' is a French term used in the context of vineyards and wine production, and French winemakers use it to refer to the complex interactions among all the physical aspects of geology, soil, climate, geomorphology and vegetation, but also in combination with the people involved, which together create a particular place or terroir, where grapes are grown (e.g. *Unwin* 2012). *Vaudour* et al. (2015) summarized the main environmental factors, namely climate, geology, geomorphology and soil, which make up the terroir effect on different scales. Moreover, human factors are part of terroir. These include history, socioeconomics, viticultural and oenological techniques (*Seguin* 1986). Basically, the so-called 'concept of terroir' relates the sensory attributes of wine to the environmental conditions in which the grapes are grown (*van Leeuwen* and *Seguin* 2006). A grape variety may produce completely differently tasting wines depending on climate (temperature, precipitation), however, some of the world's greatest wines come from a small parcel of land or in the case of so-called crus classés, subsites with varying soils planted with compatible cultivars. Human interaction (e.g. clonal selection, canopy management, irrigation, timing of harvest) is another key factor (*Bohmrich* 1996). *Van Leeuwen* and *Seguin* (2006) outlined that soil, along with climate and grapevine, are the main terroir factors, which interact with regard to vine water uptake conditions, a key factor in understanding the effect of the terroir on grape quality potential. Soil is essential as its structure regulates water, and it is apparent that soil plays a vital role for vine growth as well as for terroir.

Soil structure is the size, shape and arrangement of solid particles and voids, it is highly variable and linked by a complex set of interactions between mineralogical, chemical and biological factors (*Letey* 1991). Soil structural development is controlled by factors like texture (particularly clay), organic carbon (OC), (micro-)organisms, and land use. Finally, soil structure provides the frame for life and growth in and on soil. When it comes to vine growth and wine production, a variety of soil characteristics are important. The type of soil has an effect: vines are vigorous and highly productive in deep, rich soils, but better wines are often produced from vines cultivated on poor soils (*van Leeuwen* and *Seguin* 2006). Soil influences vine mineral nutrition, but also rooting depth (which may extend beyond the soil though) and temperature in the root zone (ebd.). Soil pH is also important, as values below 5.5 or above 10 are deemed too acidic or too alkaline to sustain grape-growing activity (*Neirynck* 2009, as cited in *Burns* 2012). The color of the soil is of relevance as it affects the temperature of the soil; the darker the soil, the warmer the soil temperatures and the faster the maturation of the grapes (*Neirynck* 2009, as cited in *Burns* 2012). Excess vigor can be the result of both, too many nutrients coming from the soil, but also too much water applied by irrigation (*Burns* 2012). Climate may determine which soil properties are desirable: in moist climates, a low soil nutrient content is desirable, whereas in dry climates, water availability should be restricted irrespective of the soil nutrient status (*Burns* 2012).

The objective of this study is to investigate the evolution of soil structure and related soil properties in a desert vineyard with a special focus on soil management and the impact on vine growth. To achieve this, field measurements were made on unmanaged sites as well as managed ones of different age, an interview was conducted, samples were collected for laboratory analyses, and additional information was researched online.

2. Material and methods

2.1 The vineyard

The Neuras vineyard is located in Namibia at 24°27′44.94″ S and 16°14′13.26″ E, close to the Tsauchab River, along a fault line, where natural springs provide water for irrigation purposes all year-round. Beginning in 1896, *Ernst Hermann*, a gardener, planted vegetables, cereals and table grapes; after 100 years and many changes also in ownership, *Allan Walkden-Davis* bought the estate in 1996 (*Badenhop* 2016). *Hermann* was of German origin, so his vineyard may be referred to as a colonial heritage (*Banks* and *Overton* 2010). As of 2011, the new owner (the N/a'an ku sê foundation) turned the farmland into a wildlife sanctuary. Besides wine production it now also relies on tourism.

Neuras features four plots established in 1997, one was added in 2013 (*Fig. 1*) by the new owner, the N/a'an ku sê foundation. All plots are irrigated, the older plots by flood irrigation and the younger plot by drip irrigation. The presence of the springs also led to the name, Neuras, which means *place of abandoned water* in the local Koikoi language (*Beardsall* 2008; *Neuras Vineyard* 2020). After pruning in July, flowering takes place from late September to November, grape formation from late November to mid-January, and finally harvest in January or February, which is approximately three months later the harvest date in the surrounding vineyards of table grape producers (*New African Frontiers* 2019). Plant residues are left on the ground and serve as fertilizer.

The grape varieties grown at Neuras include Shiraz, Merlot, Petit Verdot, Mourvedre and Grenache (plots 1–4 in *Fig. 2*). Apart from wine, brandy and port wine are produced.

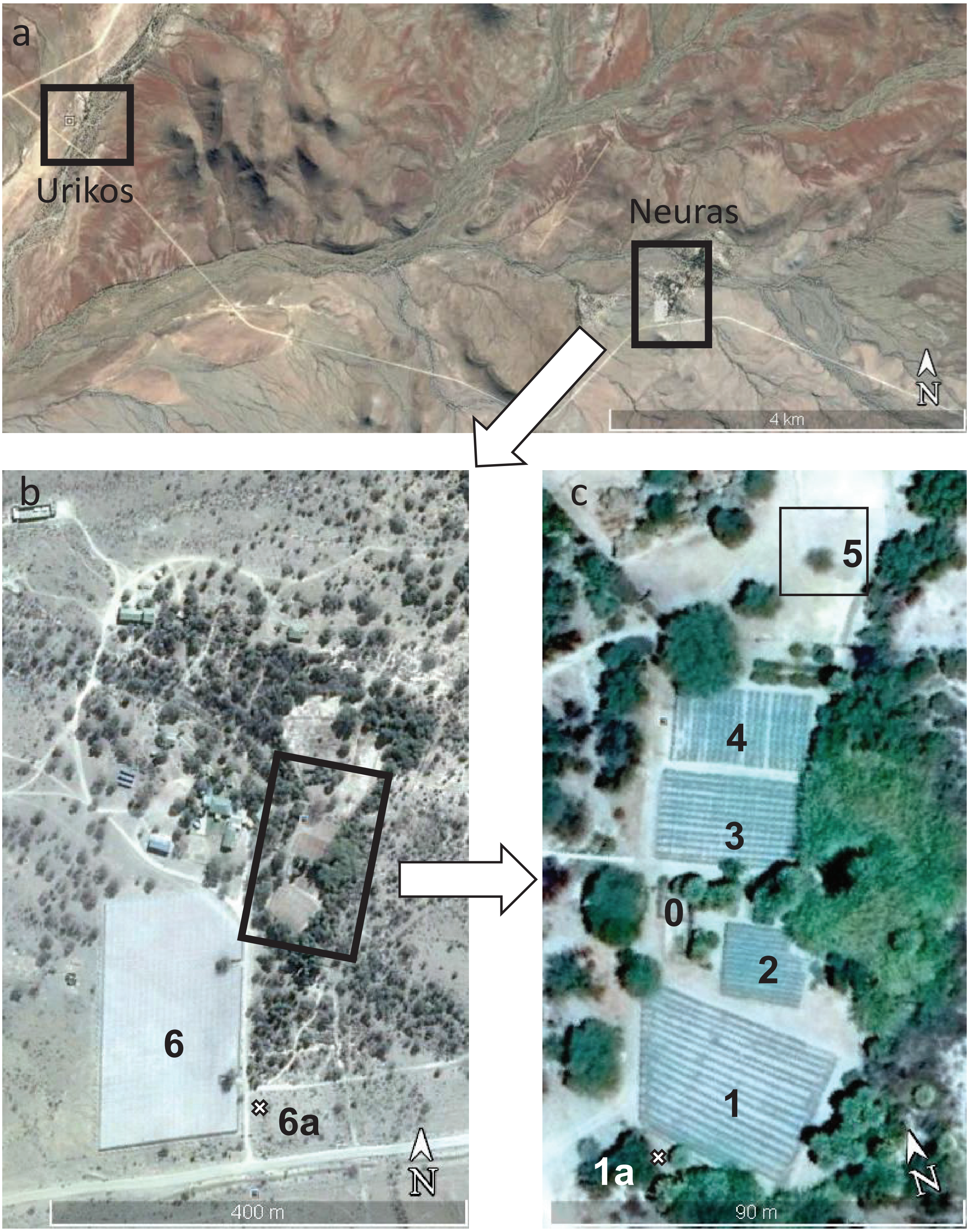

Fig 1 *Panel a: sampling plots and spots at Neuras and Urikos (image taken on 27.7.2016); panel b: Neuras and the more recent vineyard (6) and spot 6a (image taken on 27.7.2016), and panel c: the oldest plot (0), plots 1–4 established in 1997, spot 1a and the reference area (5) (image taken on 4.12.2014). Source: imagery from Google Earth and own drawing*

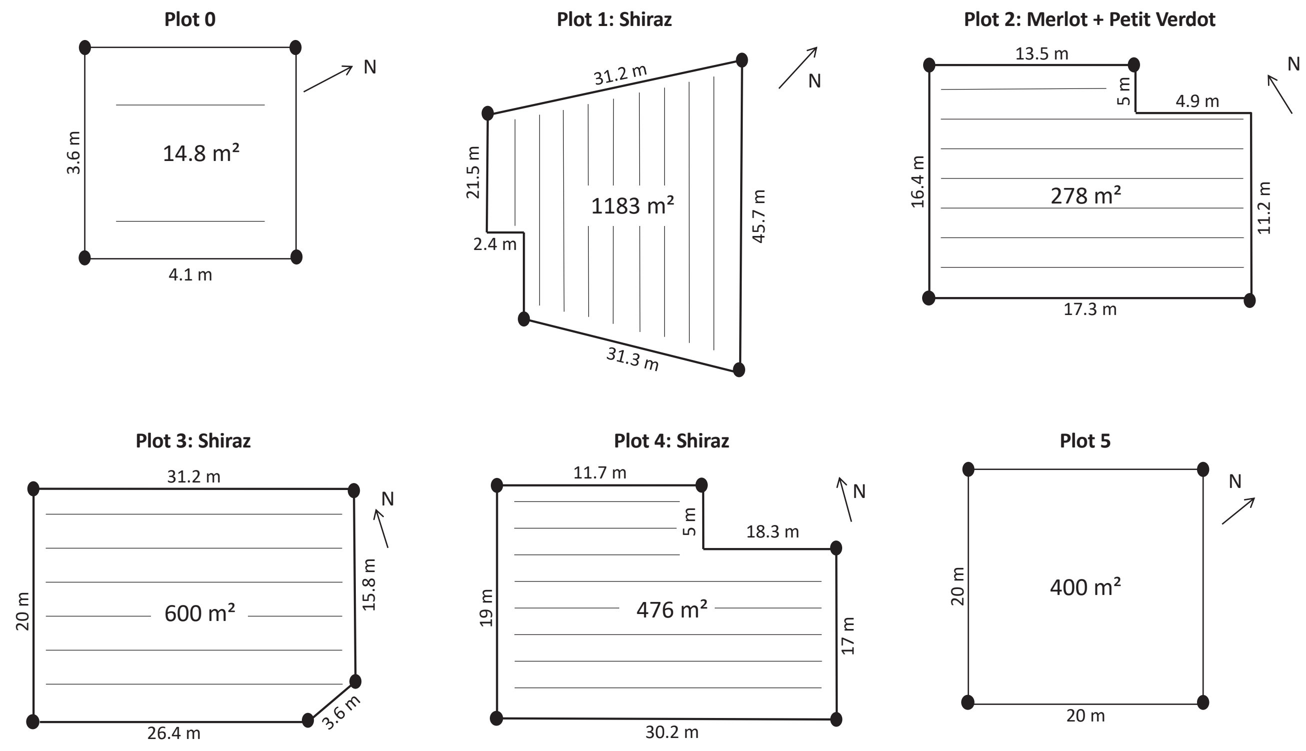

Fig. 2 Schematic detailed sketches of plots sampled in 2016 including area in m^2. Source: own drawing

2.2 Geology

The sedimentary rocks in the research area are dominated by the Kuibis Subgroup in the Southwest and the Schwarzrand Subgroup in the Northeast of Neuras vineyard, both part of the Proterozoic Namibian Nama Group representing a foreland succession and basin filling (*Grotzinger* and *Miller* 2008). While the Schwarzrand Subgroup around the locality consists of green and red Nama shale and quartzite, the Kuibis Subgroup comprises carbonates, limestones as well as shale. Caused by the Damaran regional metamorphism all sedimentary rocks are rich in fine-grained white mica. The generally siliciclastic rocks of both subgroups such as sandstones are rich in quartz with up to 20% feldspar dominated by albite with subordinated microcline, some plagioclase altered to chlorite. Illite is found in the matrix. The usually green mudrocks are composed of quartz, muscovite, albite, chlorite and some calcite (*Blanco* et al. 2011). Additionally, the Schwarzrand Subgroup contains montmorillonite.

Generally, vine stocks root deeply in the subsoil and hard rock. Therefore, the pedogenetic status of any potential vineyard is not of basic interest. Naturally, soil development is restricted in this desert environment. Slope sediments cover the rocks by several decimeters, consisting of debris. In most cases, these sediments are the substrate for soil development. Physical and biogeochemical weathering processes formed a soilscape of reddish-brownish Leptosols and Regosols (*Jones* et al. 2013; *Völkel* et al. 2016), showing initially cambic features and aggregates.

2.3 Climate

Following the climate classification scheme of *Köppen* and *Geiger* (cf. *Kottek* et al. 2006), the investigation area is situated in the BWh zone characterized by a hot desert climate. The seasonal (November to April) average annual precipitation is 135 mm (1972–2017) measured at the neighboring farm at Urikos (*Fig. 3*; *Johan Steyn*, personal communication, Tsauchab Rv. Camp, November 2017). We consider these data as reliable and of much higher accuracy than interpolated data published by the *Ministry of Agriculture, Water and Rural Development* (1999). According to them, the average annual rainfall in the area varies between 150 and 200 mm, while average annual temperature calculated from the average of daily maximum and minimum temperatures is around 20–21 °C, and the average rates of evaporation per year and month account for 3,400–3,600 mm/y (EVAP) or 2,380–2,520 mm/a (EVAP-30, *Ministry of Agriculture, Water and Rural Development* 1999). For further climate information see *RAISON* (2011).

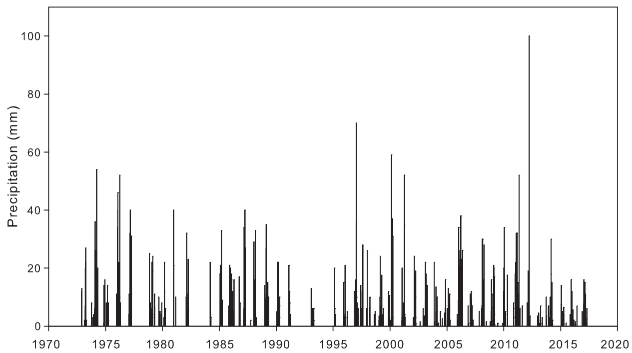

Fig. 3 *Precipitation records of the Urikos farm from 1972 to 2017. Source: own drawing based on personal communication with Johan Steyn, Tsauchab Rv. Camp, November 2017*

2.4 Sampling

Walkden-Davis established four plots, here labelled 1 through 4 (*Fig. 1*), a small plot with a vine plant of *Hermann* from 1896 is marked with 0. Within plots 1 to 4 and a reference area in unplanted open space (5) samples were taken at four randomly chosen locations and from one location in plot 0 in October 2016 at a depth of ca. 5–10 cm. Plot sizes are given in *Figure 2*. Bulk soil was taken for physical and chemical analysis, and undisturbed cores (100 cm^3, two per sampling spot) were extracted for determination of the water retention curve and related properties. This makes a total of 40 cores from 2016.

A preliminary sampling campaign in August 2014 provided bulk soil and cores from both, the older (1–4) and younger (6) vineyards, as well as shrubland adjacent to the Tsauchab River on the neighboring farm, Urikos (*Fig. 1*), from a depth of ca. 5–10 cm. Plot 6 has an area of roughly 30,500 m^2 (ca. 3 ha), plots 1–4 combined are ca. 2,500 m^2, and the sites on both farms are ca. 6.5 km apart. The older plots (1, 3 and 4) and the shrubland (Urikos) were sampled in three locations, the newer plot 6 in four. Finally, two locations outside of the older (spot 1a) and younger (spot 6a) vineyards, respectively; two samples were extracted per location. In 2014, a total of 18 samples was taken at Neuras and six at Urikos.

2.5 Field measurements

Soil moisture probes (ML2 and ML3, ThetaProbe, Delta-T, Cambridge, UK) were installed at four depths (at –10 cm, ML3; –35 cm, ML2; –58 cm, ML3; and –108 cm, ML3) in plot 3 providing information along the soil profile from October 2016 to mid-March 2017. The probe at 10 cm depth also recorded soil temperature. The data logging interval was set to three hours. The accuracy of the probes as specified by the manufacturer is 1% and 0.5 °C, respectively. Soil moisture at the surface of plots 1 to 4 was recorded using the ML2 probe prior to its installation at fixed distance intervals in October 2016 and again in March 2017 after its extraction. Three replicate measurements were made and the average was taken. Plot 5 could not be measured as the soil was too hard for the probe to enter. Moreover, the water drop penetration time test (*DeBano* 1981) was performed in 2014. Precipitation data were recorded on the neighboring farm, Urikos, since 1972 (*Fig. 3*) by the farm owner.

2.6 Laboratory analyses

The water retention curve of samples from 2016 was determined with HYPROP (*UMS* 2015) applying the simplified evaporation method (*Peters* and *Durner* 2008) for the wet range and a WP4C Dewpoint PotentiaMeter (*METER Group* 2017) in the dry range. Specific data points were approximated using the HYPROP-FIT software (*Pertassek* et al. 2015), which was further employed to model the entire range of the individual retention curves. The cores from 2014 were equilibrated at a range of moisture contents (pF 1.0, 1.3, 1.5, 1.7, 2.0, 2.3, 2.5, 2.7) using a pressure plate apparatus. At each moisture content the samples were weighed and the soil cores were furthermore used to measure bulk density. For both datasets, cores were saturated to a level just below the rim of the cores for ca. three days considering sample height and until the surfaces exhibited the shine of water.

Soil texture was analyzed following the combined pipette and sieving method of *Köhn* and *Köttgen* (clay: < 0.002 mm, silt: 0.002–0.063 mm, sand: 0.063–2 mm). The clay fraction (< 2 µm) was separated by the Atterberg sedimentation method, humics were disturbed by H_2O_2 (6%), carbonates extracted by an acid treatment (HCl) and oxides by the DCB-method after *Mehra* and *Jackson* (1960). Clay samples were saturated with a 0.5 M $MgCl_2$ solution. For preparation we used ceramic slides (Diapor G30, Schumacher Umwelt- und Trenntechnik, Crailsheim, Germany) pipetting roughly 2 ml of the treated clay suspension, treating the (i) overnight air-dried $MgCl_2$ saturated preparations with (ii) ethylene glycol atmosphere at 6 °C, preparing (iii) a potassium saturated sample (1 M KCl) followed by (iv) heat treatments at 200 °C, 350 °C, and 550 °C (interim stages if needed) in a muffle furnace. We used a Siemens D 5000 X-ray diffractometer for mineralogical analyses with Co-Kα radiation at 45 kV and 40 mA, scanned from 2° to 32° 2 Theta with a position-sensitive detector and anti-scatter slit. For more information see *Völkel* (1995: 23-25). Soil pH was measured potentiometric in 0.01 M $CaCl_2$ at a ratio of 1:2.5 after 30 min and 24 h. Soil Electrical Conductivity (EC) was measured conductometrically in aqua bidest at a ratio of 1:2.5. Total carbon (C) and total nitrogen (N) contents were determined using an Elementar Vario EL III. The effective cation exchange capacity (CEC) was measured with an atomic absorption spectrometer (Thermo Scientific™ iCE™ 3000 Series) after the sample was mixed with 1 m NH_4Cl dissolution. Carbonate contents were derived with the gas volumetric Scheibler method (Calcimeter) and used to calculate the contents of inorganic carbon (IC). Due to the geological setting no dolomite was expected and moreover, calcite is the most common carbonate found in soils, therefore, the results from the Scheibler method were used to calculate inorganic carbon. The content of organic carbon (OC) was inferred from total (TC) and inorganic carbon (*Prietzel* and *Christophel* 2014). For the stable isotopes of carbon two measurements were made per sample collected in 2014, provided it contained organic carbon, the average was used to infer $\delta^{13}C$.

2.7 Digital elevation model

A GFZ/DIMAP airborne campaign (project NA201502) on 5 June 2015 provided Airborne Light Detection and Ranging (LiDAR) data acquired with a Riegl LMS-Q780 Q780 long-range airborne laser scanner from approximately 2,850 m above ground level under cloud and fog free conditions. Strips of 3 km width, overlapping by ca. 60%, with an averaged point density of 2.1 pts/m^2 were recorded, in total 11 flight lines (six from SE to NW, and five from SW to NE). Calibration flights indicated an accuracy of ±10 cm in vertical and ±15 cm in horizontal directions (95% confidence level). For the area around Neuras a 1-m-grid Digital Elevation Model (DEM) in meters above sea level (a.s.l.) was created with the TerraScan software by Terrasolid (Helsinki, Finland) to process LiDAR data and produce 3D vector data. The first return LiDAR mass point data were converted to a Triangulated Irregular Network (TIN) surface mesh and further to a regular raster grid with natural nearest neighbor interpolation. More information on this project can be found in *Milewski* et al. (2017).

2.8 Statistical analysis

Non-metric multidimensional scaling (NMDS) was performed to graphically display the dissimilarities of all sites using the vegan package (*Oksanen* et al. 2019) in R (*R Development Core Team* 2008) and a large set of variables. The number of dimensions needed is assessed with the classification provided by *Everitt* and *Hothorn* (2011), where a stress value close to 0 is perfect, and considered good if it is between 0.1 and 0.05. Each sampling spot is represented by an open circle and the distance of spots within and between plots shows how dissimilar they are with regard to the original variables used. Far away circles are less similar with regard to the variables investigated while nearby circles are more similar to each other regarding.

3. Results and discussion

3.1 Detailed site description

An aerial survey was performed along Tsauchab River and Neuras in 2015 and delivered a high-resolution (1 m) digital terrain model (DTM) of the area. For Neuras and particularly the older vineyards, *Figure 4* shows the location of plots 0 to 5 at approximately 1,225 m a.s.l., whereas plot 6 lies at an elevation of ca. 1,227 to 1,231 m a.s.l. The older plots hence lie in a location more likely covered by sediments, whereas plot 6 is more prone to erosion, as rainwater might run off rather than infiltrate. *Figure 2* provides a precise overview of the sizes of plots 0 to 5.

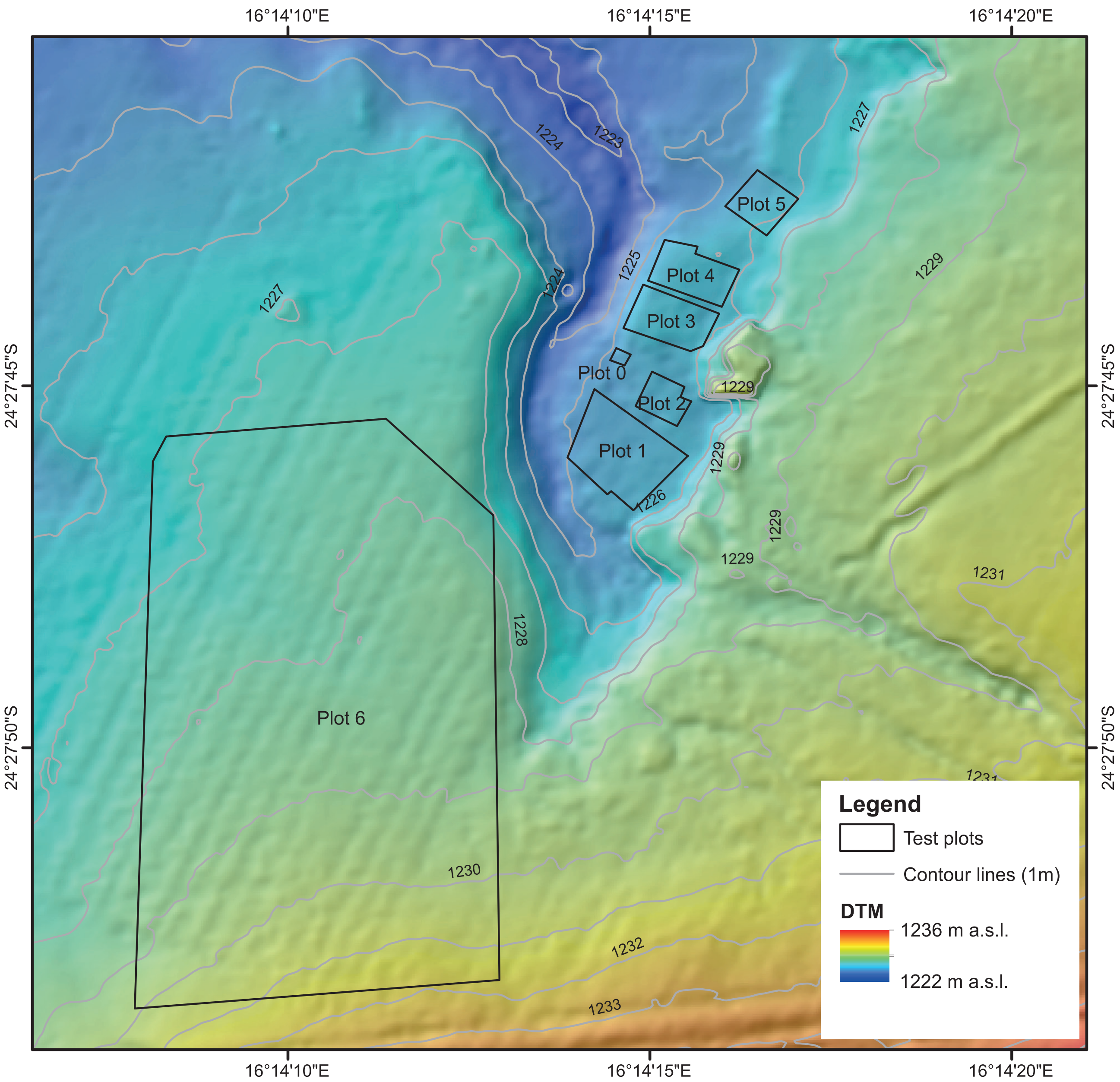

Fig. 4 Digital terrain model (DTM) of the Neuras vineyards and reference plot 5; resolution: 1 m. Source: own drawing

3.2 Basic physico-chemical soil properties

A bed of rock sloping towards the river bed on the farm was found at ca. 1.8 m depth (*Beardsall* 2008), above it the soil, which *Jones* et al. (2013) classifies as reddish-brownish Leptosols and Regosols. For Urikos the colour was determined as strong brown, in Neuras it varied, at 1–4 it was (dark grayish) brown, at 1a the color was dark yellowish brown, at 6 (yellowish or reddish) brown and at 6a reddish brown.

Differences were observed between plots and years. Regarding basic soil properties, similarities and differences between plots as well as between years are shown in *Tables 1* and *2* and *Figure 5*. Plots 0–5 in the bottom of the valley have similar textures: clay ranges from 12.9 to 19.9%, silt from 37.4 to 52.1% and sand from 33.7 to 49.8%; gravel (> 2 mm) content varies between 7.9 and 16.5% (*Table 1*). The new vineyard (6) has a lower silt content and a larger sand and gravel content, which overall is more similar to the shrubland soil at Urikos (*Table 2*). Bulk density increases in the order of 0 < 1 < 4 < 2 < 3 = 5 < 1a < 6 < 6a < Urikos, while total porosity displays the opposite order (with 6a = Urikos) (*Tables 1* and *2*). Total carbon (TC) is much lower in plots 6, 6a, and Urikos. For carbonates the largest value was found in plot 5 (52.8%), the lowest in Urikos (2%). Plots 6 and 6a displayed lower values than plots 0 to 5 and the average value of plots 1–4 in 2014 was lower than the values recorded in 2016 (*Tables 1* and *2*). Organic carbon (OC) was slightly higher for the average of 1–4 in 2014, in 2016 it was highest in plot 0, similar for 1–4 and slightly lower in 5; plot 6 and Urikos showed markedly lower values (*Tables 1* and *2*). For total nitrogen (N) values from 2014 and 2016 are in good agreement; plot 0 has the highest value, plots 1–5 are fairly similar, plot 6 and Urikos showed markedly lower values (*Tables 1* and *2*). pH was slightly lower in 2014 and overall ranged between 7.8 and 8.5. Electrical conductivity (EC) in 2014 was far higher in Urikos than in Neuras and spot 1a stands out with a much higher value within Neuras; in 2016 values were fairly uniform in the managed plots, while plot 5 displayed a far lower value. Cation exchange capacity (CEC) was markedly lower in 2016: in 2016 plot 5 stood out with the highest value, while in 2014 Urikos displayed the lowest (*Tables 1* and *2*). The evolution of soil properties with depth is exemplified in *Table 3* for a soil profile in plot 3. The texture below the surface is coarser, both N and TC as well as carbonates and OC, are lower. Plot 5 may equally have a deeper soil profile akin to that of the older plots, however plot 6 is likely much shallower and contains far more gravel (*Table 2*) and less soil material (< 2 mm). Regarding water repellency, the water drop penetration time test revealed that water infiltrated the soil immediately without any delay, the soil surface presents no hydrophobic properties in any of the sites investigated in 2014 (plots 1, 3, 4, 6, spots 1a and 6a, and Urikos).

Table 1 Physico-chemical properties of the surface soil in plots 0–5 in October 2016. Source: own measurements (Results for bulk density and total porosity are based on n=8 samples from plots 1–5 and n=2 from plot 0)

	Clay % < 2 µm	Silt % 2–63 µm	Sand % 63–2,000 µm	Gravel % > 2 mm	Bulk density g/cm^3	Total porosity cm^3/cm^3	Total Carbon %	Carbonates %	Organic Carbon %	Total Nitrogen %	pH $CaCl_2$	EC mS/cm	CEC mmol/kg
Plot 0	14.3	52.1	33.7	7.9	1.11±0.01	0.58±0.00	8.8	48.6	3.0	0.33	7.9	0.54	23.9
Plot 1	12.9±1.0	37.4±14.3	49.8±14.7	16.5±7.0	1.14±0.13	0.57±0.05	7.7±0.8	44.3±6.6	2.3±0.9	0.20±0.12	7.8±0.1	0.49±0.1	22.3±3.5
Plot 2	14.3±1.3	38.2±3.8	47.6±5.0	13.4±6.7	1.27±0.04	0.52±0.02	7.7±0.2	45.5±2.8	2.3±0.2	0.21±0.02	7.9±0.1	0.51±0.0	22.3±0.6
Plot 3	17.0±4.7	47.0±7.3	36.0±2.8	12.2±1.9	1.31±0.07	0.51±0.03	8.1±0.5	48.7±3.6	2.2±0.2	0.23±0.02	7.9±0.1	0.46±0.0	25.3±3.4
Plot 4	19.9±1.9	42.3±4.7	37.8±3.0	13.1±3.7	1.24±0.04	0.53±0.02	8.0±0.4	44.9±4.6	2.6±0.4	0.26±0.04	7.8±0.1	0.51±0.1	24.2±3.7
Plot 5	14.6±0.7	45.3±7.0	40.1±7.3	16.0±11.2	1.31±0.04	0.51±0.02	8.3±0.4	52.8±5.4	2.0±0.8	0.21±0.03	8.2±0.4	0.01±0.0	33.9±8.4

Table 2 Physico-chemical properties of the surface soil in and next to the older and younger vineyards, and at Urikos in August 2014. Source: own measurements (Results for bulk density and total porosity are based on n=6 samples from Urikos and plots 1–4, n=8 from plot 6, and n=2 from spots 1a and 6)

	Clay % < 2 µm	Silt % 2–63 µm	Sand % 63–2,000 µm	Gravel % > 2 mm	Bulk density g/cm^3	Total porosity cm^3/cm^3	Total Carbon %	Carbonates %	Organic Carbon %	Total Nitrogen %	pH $CaCl_2$	EC mS/cm	CEC mmol/kg	$\delta^{13}C$ ‰ accuracy ±0.5‰
Plots 1–4	13.9±2.5	41.3±6.0	44.8±7.8	14.6±0.4	1.26±0.03	0.52±0.01	7.4±0.6	34.5±5.2	3.2±1.1	0.21±0.1	8.4±0.0	0.36±0.1	49.4±4.0	-22.55 (n=6)
Spot 1a	6.1	30.8	63.1	34.2	1.45±0.18	0.45±0.07	6.2	26.4	3.0	0.18	8.3	0.34	43.4	-22.90 (n=2)
Plot 6	14.8±5.6	23.8±1.6	61.4±7.1	46.8±17.7	1.52±0.08	0.43±0.03	2.9±1.6	16.3±8.8	1.0±0.6	0.06±0.0	8.5±0.1	0.26±0.1	40.7±2.6	-18.88 (n=4)
Spot 6a	9.1	28.3	62.6	30.3	1.74±0.03	0.34±0.01	2.3	13.4	0.6	0.05	8.4	0.24	44.9	-18.99 (n=2)
Urikos	20.4±0.8	21.8±6.0	57.8±6.9	35.8±15.1	1.69±0.06	0.36±0.02	0.6±0.3	2.0±2.1	0.4±0.3	0.06±0.0	8.2±0.4	6.26±6.1	34.4±11.1	-19.01 (n=6)

Table 3 Physico-chemical properties of the soil profile in plot 3 at four depths. Source: own measurements

Depth cm	Clay % < 2 µm	Silt % 2–63 µm	Sand % 63–2,000 µm	Gravel % > 2 mm	Total Carbon %	Carbonates %	Organic Carbon %	Total Nitrogen %	pH $CaCl_2$	EC mS/cm	CEC mmol/kg
0–20	8.1	53.6	38.3	11.8	7.3	46.4	1.7	0.18	7.8	0.4	24.7
20–40	21.2	35.1	43.7	20.2	5	34.7	0.8	0.08	7.8	0.25	24.0
60–80	20.3	31.8	47.9	25.0	5.1	38.6	0.5	0.05	8	0.29	22.5
80–108	20.8	34.5	44.7	30.5	4.5	35.3	0.2	0.05	8	0.35	24.4

In terms of physico-chemical properties, plot 0 displayed the most beneficial conditions for plant growth, followed by plots 1 to 4. Plot 5 appeared rather similar to plot 3 for bulk density and total porosity; however, it differed from all other plots in terms of OC, carbonates, pH, and even more pronounced for EC and CEC. In 2014 the soil properties of plot 6 (and spot 6a) indicated very different conditions for this younger vineyard in comparison with the older ones. The properties of plot 6 were more similar to those of the shrubland at Urikos, however, also here certain differences were observed, i.e. regarding bulk density and porosity, TC and carbonates, EC and CEC. For N the values found for Urikos, plot 6 and spot 6a correspond well with those found for surface soils of gravel plains and sand dunes (53 samples; mean: 0.019% N and max 0.06% N) of Central Namib (*Ramond* et al. 2018), while those of the older plots lie well above. For TC *Ramond* et al. (2018) documented values in the range of 0.07 to 0.41% C (mean: 0.12% C), which is similar to the value found at Urikos, being the lowest within this study. The comparison between years is limited to plots 1–4. In this respect differences can be observed particularly for carbonates and OC, pH, EC and CEC. The properties overall indicate a suitable soil for plant growth. The vineyard soils have rather low bulk densities and consequently high porosities, which also becomes obvious in comparison with the Urikos soils. Also the OC level of these soils is much higher. Soil pH, which is important in terms of availability of several nutrients and for root growth (extremes in pH inhibit it; *White* 2015), is at a satisfactory level.

The $\delta^{13}C$ measurements on samples from 2014 varied from –18.06 to –22.95‰ (±0.5‰ accuracy, *Table 2*). The shrubland on the neighboring farm Urikos showed values ranging from –18.06 to –19.82‰, which was similar to the values of the younger vineyard (plot 6) with –18.31 to –19.45‰ (determination only possible for two of the four spots, for which organic carbon was detected) and the spot just outside of it (6a) –18.99‰. However, the older vineyards (plots 1–4) and the spot just outside of those (1a) displayed values of –21.86 to –22.95‰ and –22.90‰, respectively. Regarding $\delta^{13}C$ the soils in and near the older vineyards are likely affected by a larger input of biomass from vines, a C3 plant yielding plant matter with –25‰ to –27‰ (*Bird* et al. 2004), over nearly two decades. The younger vineyard, which had just been established a year before, and the shrubland displayed a much sparser vegetation of new vines or grasses (C4 plants) and small shrubs, respectively. *Bird* et al. (2004) found larger negative values under wetter conditions (which reflects an increasing dominance of C3 vegetation) for a climate gradient from Southern Botswana into southern Zambia; in the driest area with a mean annual precipitation of 225 mm $\delta^{13}C$ was –17.5‰. In the present study area the mean annual precipitation is even lower than in *Bird* et al. (2004), however, $\delta^{13}C$ values are slightly more negative. Central Namib surface soils on average displayed values of –18.3‰ (*Ramond* et al. 2018), which is similar to the plots and spots that did not (yet) have the additional input of C3 plant material from vines.

Using two dimensions for the NMDS a stress value of 0.093, which can be considered ‘good’ was achieved. Increasing the number of dimensions decreased the stress value, however, the differentiation within and between plots and spots is also discernible with two dimensions and suitable for the purpose of visualizing the dissimilarities of the plots, which can also be seen from *Tables 1* and *2*. *Figure 5* shows that while plots 0 to 5 are partially overlapping and hence display some similarities, plots 1a, 6a, 6 and U (Urikos) differ from 0 to 5. Especially plots 6a, 6 and U differ in terms of final bulk density, CEC, sand content, as well as clay content and pH from the other plots. *Figure 5* further indicates the heterogeneity within the plots, particularly 1 and 6, but also 2 and 5, where the individual soil cores (and related bulk soil data) are quite different from one another. The soil cores from Urikos on the other hand are more homogeneous in comparison. For plots 0, 1a and 6a the large similarity of both soil cores was expected due to the proximity of sampling.

3.3 Clay minerals

When establishing the vineyards the reddish-brownish Leptosols and Regosols were ploughed and prepared for planting. Both, irrigation and soil management forced the weathering and pedogenic transformation processes. Most sensible indicators to that effect are the phyllosilicates within the clay fraction (< 2 µm), so-called clay minerals. We investigated 30 soil samples from 15 soil pits covering all types of vine fields from the first steps in 1894 up to the vineyard established in 2013. Generally, all spectra are rich in Chlorite, Illite (mica) and swellable minerals of the Smectite group. Quartz and feldspars are also present. The long-term managed soils show a higher content of Smectites and Vermiculites at the expense of Chlorites as well as Illites. Likewise, the notice-

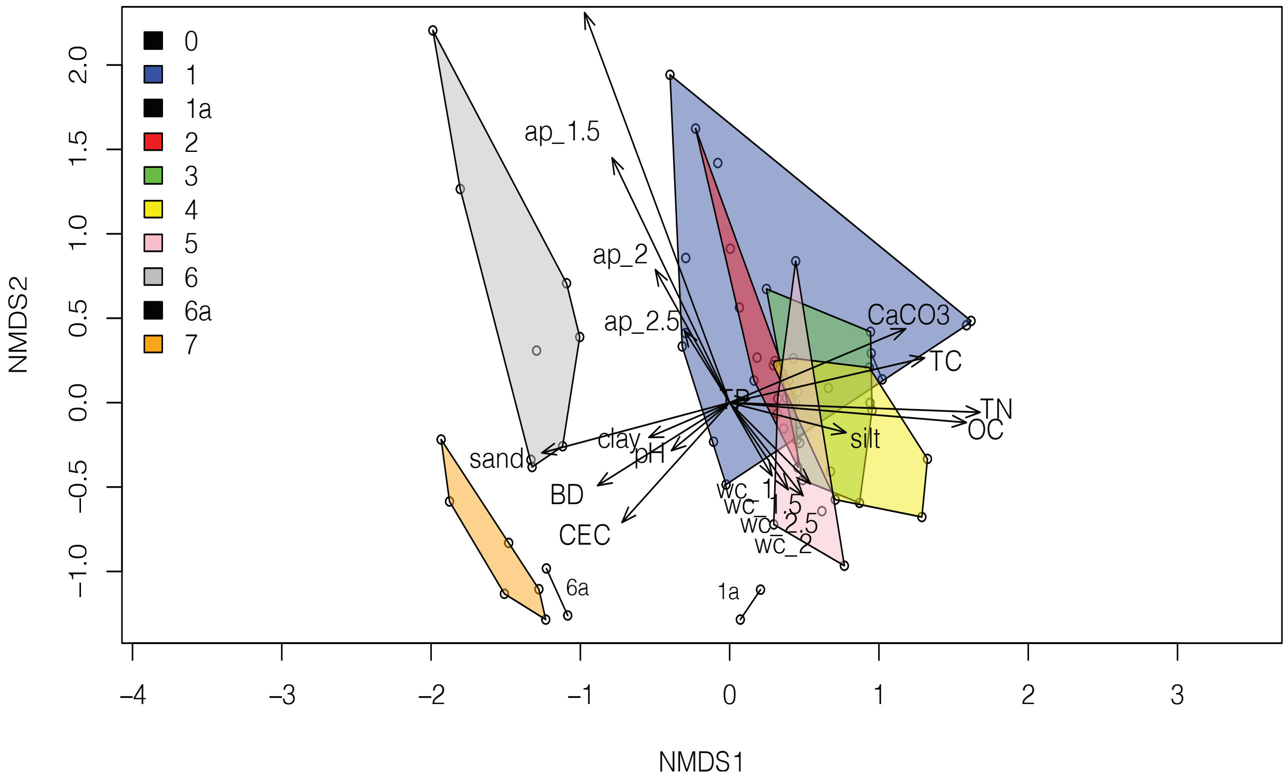

Fig. 5 *Non-metric multidimensional scaling (NMDS) of all plots and spots with two dimensions, NMDS1 and NMDS2. Soil cores (and related bulk soil data) are indicated as open circles. For plots 1–6 and 7 (Urikos) they are connected forming differently-shaped areas. Plot 0 (just below label $CaCO_3$) and spots 1a (close to "0" on x-axis) and 6a (next to 7, Urikos), in which less samples were taken, are displayed with a line connecting the points. A large number of variables was used to display the dissimilarities of the plots and spots: ap_1.5 is air-filled porosity at pF 1.5 etc., wc_1.5 is volumetric water content at pF 1.5 etc., BD is bulk density, TP is total porosity, further variables are sand, silt, clay, CEC, pH, $CaCO_3$, OC, TC, and TN. The variables are given as arrows, labelled accordingly. The arrow extending towards the top of the figure is that of ap_1; wc_1, wc_1.5, wc_2 and wc_2.5 are covering each other. Source: own drawing*

able high content of mixed-layered minerals from 1.4 to 1.7 nm base distance between the primary layers underlines these findings. In contrast soil samples taken from the youngest vineyard soil do not contain any swellable minerals (in the range of 1.4 to 1.7 nm) but are dominated by primary Chlorites, which are completely absent in all other managed soils while the neighboring natural soils show high contents of Chlorite as a component of rock minerals. From an agricultural point of view both rocks and their slope sediments as first weathering products on one hand and the natural as well as the managed soils on the other offer a rich spectrum of clay minerals with best features such as bonding properties for water and nutrients, aggregate stability and many others. Again, plot 6 stands out in comparison with plots 1–4.

The key factors of soil structure and its development, clay and organic carbon, are quite similar in plots 0–5, however, plot 5 has a slightly lower OC content and moreover a different management history, which may explain, e.g., the different surface soil conditions observed in the field during soil moisture measurements. Plot 6 varies in terms of OC content, irrigation management and also clay content, in regards to its ratio with gravel in a given soil volume (e.g. 100 cm^3). Hence a different soil structure, which in turn influences related soil properties was expected and confirmed.

3.4 Soil structure and soil water

At Neuras, water from on-site springs is used to irrigate the vineyards; without this source of water a vineyard would not be possible. Surrounding farms do not grow any crops, and instead rely on livestock, game or tourism (*Völkel* et al. 2018). The amount of water used for flood irrigation, which is usually done on Saturdays, is ca. 55,000 l per week. Drip-irrigation in plot 6 is conducted daily except for Saturdays and reaches ca. 45,000 l per week (3 l/h and 15,000 dippers / plants). The springs provide ca. 78,000 l/d. *Miller* et al. (2013) outline that groundwater in the Namib Naukluft region only recharges with heavy storm events when water infiltrates faster than it evaporates. They continue to point out that the groundwater system is vulnerable to over abstraction and contamination, e.g. the Tsauchab River catchment displays increased EC values. These springs were studied upon request of the vineyard manager to find out about future water availability. While some springs are likely to eventually dry out, others are expected to continue to provide water for a long time (*Iván Phillipson*, personal communication, 10/2016). Moreover, the spring water itself was investigated, revealing that it is of good quality and, e.g., complies with German drinking water quality; the groundwater table is at a depth of 7 m (*Bemlab Laboratory*, personal communication, 03/2017). A separate study revealed, that spring water taken in February 2009 from Fountain 3 (24°27′40.10″ S, 16°14′22.24″ E) has a ^{14}C age (UNIL) of 1202 years before present (*Naudé* 2010). According to *Badenhop* (2016), the spring water is 1800 years old.

Plot 3 was equipped with soil moisture sensors at four depths (*Fig. 6*) and soil properties were also characterized at each depth (*Table 3*). Soil texture is rather similar below 20 cm depth, but the uppermost layer differs. The amount of particles larger than 2 mm increases with depth from 12 to 30%. Total and organic carbon decreases with depth, also Nitrogen content is especially high in the topsoil, while pH and CEC are rather similar throughout the entire profile. Observations regarding clay and OC contents confirm the expectable different conditions for soil structure throughout the soil profile. The recurring events of flood irrigation can be seen in *Figure 6*, which shows the evolution of volumetric soil moisture within the profile and soil temperature near the surface. The peaks seen at 10 cm depth indicate an irrigation event. Subsequently the soil dries out until more water is added. At depths of 35 and 58 cm these peaks initially are not as pronounced, however, later in the season, from December on, also in those depths, the peaks of irrigation events are visible as is the subsequent drying of the soil. Roots in this layer can benefit from and extract this water. The soil around the lowest probe, installed at 108 cm depth, remains unaffected by the irrigation throughout the observation phase. Hence, roots at this depth and below are not directly bene-

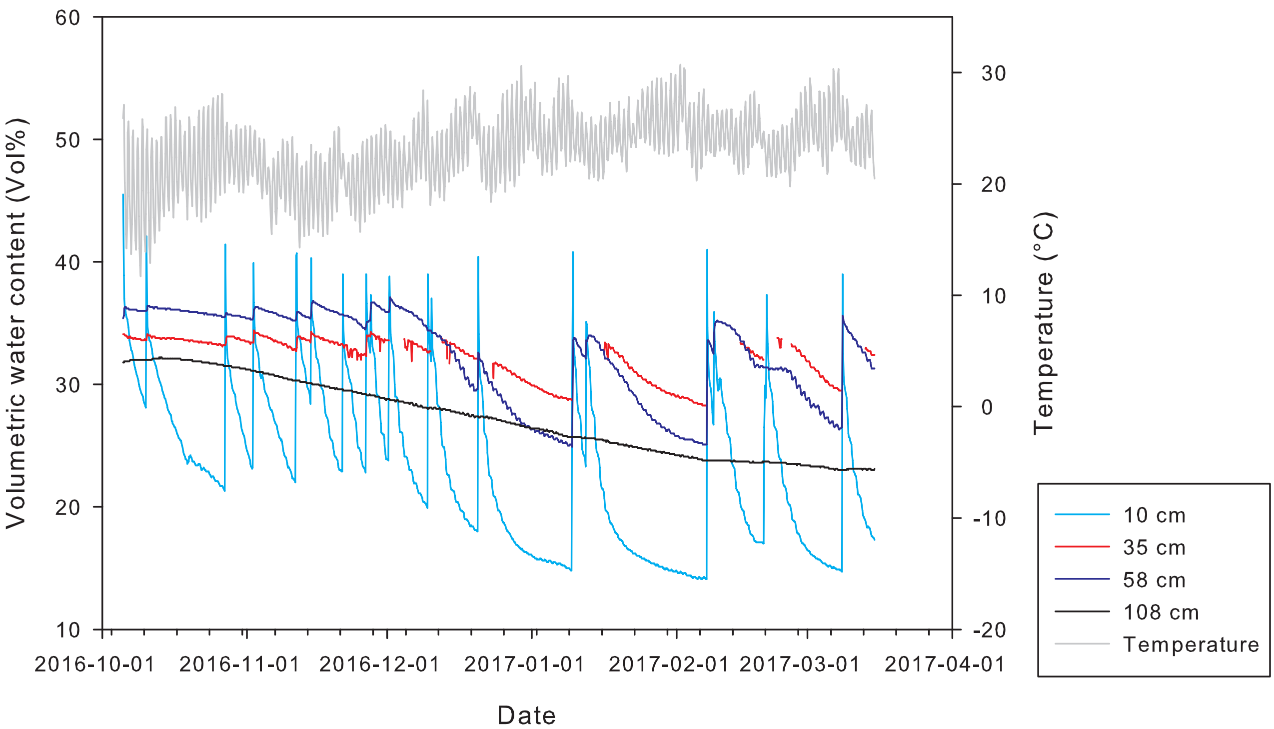

Fig. 6 Volumetric soil moisture in cm³/cm³ measured in four depths and soil temperature (°C) at –10 cm as recorded in plot 3 from October 2016 to March 2017. Source: own drawing

fiting from the recurring flood irrigation. It dries out from initially 32 to eventually 23 Vol-%. The range of soil moisture encountered by the uppermost probe in comparison is 46 to 14 Vol-%, on average the soil moisture is 20 Vol-%, while the lower depths all display an average value of 30 Vol-% throughout the growing season. At 10 cm depth the soil temperature ranges from 11.7 °C to 30.7 °C with an average of 23 °C. Flood irrigation provided sufficient amounts of water to ensure that not all was lost to evaporation and that instead water was infiltrating into the soil. Nonetheless, in irrigated vineyards rooting depth and consequently water availability at lower depths is less important as irrigation is used to control the water content in the top 50 cm of soil only (*White* 2015). Looking at *Figure 6* and *Table 4* it becomes apparent that soil water content in 10 cm depth starts out wetter than field capacity (FC) and does not quite reach the permanent wilting point (WP), which means water stress would be modest. At greater depths (35, 58 and 108 cm) volumetric soil water content does not go below 20 Vol-%, which means that roots and consequently vines in the top 1 m of soil are presumably not exposed to water deficit.

The soil moisture content at the surface in plots 1 to 4 was measured once in spring (October 2016, *Fig. 7* left) and once in fall (March 2017, *Fig. 7* right). Plot 5 was not measured as the soil was either extremely hard (probe could not be pushed in) or too loosely-packed (contact problems for the sensor). In spite of the mutual irrigation schedule in October 2016 the plots display a fairly large variation (37.5 Vol-%) among and within plots. Plot 1 has the largest within-plot variation and is on average the driest. This is in contrast with plot 3, which is the moistest. Plots 2 and 4 are comparatively homogenous (rather low within-plot variability) and display overall intermediate values. In March 2017 differences among and within plots are large as well. The total variation is even larger with 41.4 Vol-%. Plot 3 displays the largest within-plot variation (35.4 Vol-%) and is the moistest, as in 2016, while plot 1 is the driest, as in 2016. Plot 1 is fairly homogenous displaying the smallest range of values measured; also plots 2 and 4 are rather homogenous again. In 2017 along with the soil moisture also soil surface temperature was measured. Plots 2–4 displayed lower temperatures (means 27.8–31.4 °C) and in plot 1 the highest values were recorded (mean 39.8 °C).

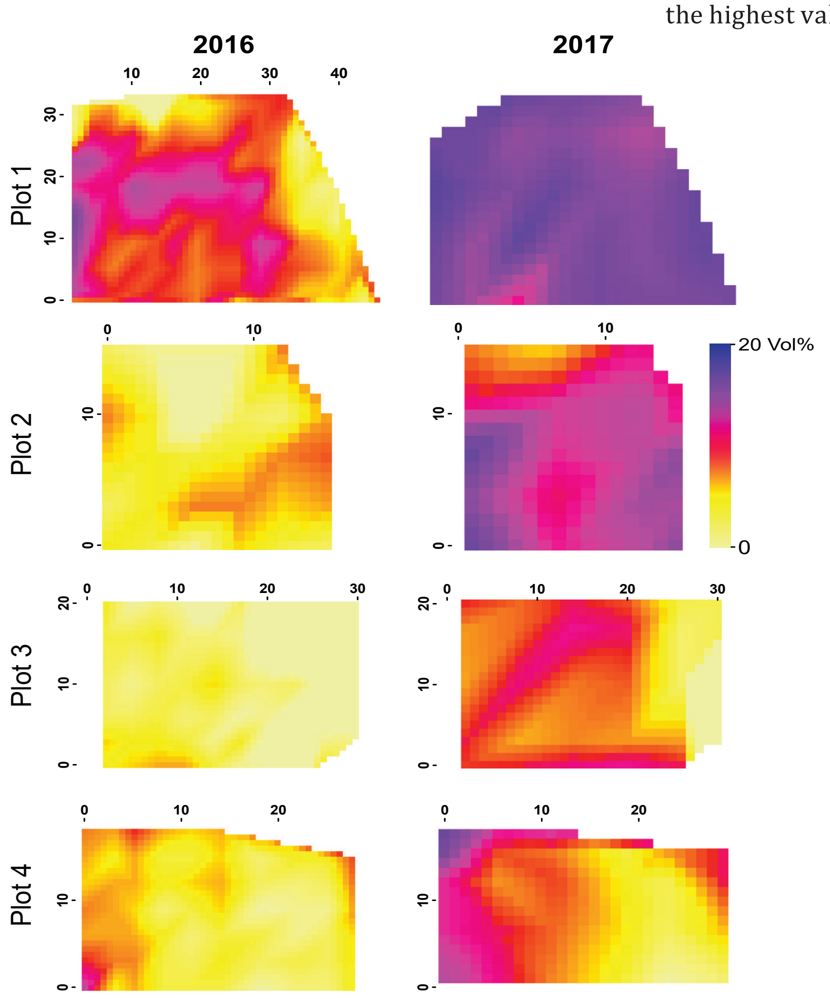

Fig. 7 *Soil moisture (Vol-%) at the surface in plots 1 to 4 (given in m) measured in October 2016 (left) and March 2017 (right). The interpolation method applied is triangulation using the mean of three measurements per spot. Note that the moistest spots are ≥ 20 Vol-%, the generalized scale allows for comparison among plots and years. Source: own drawing*

Soil structure determines the water retention curve, as bulk density / total porosity delineate the pore volume available for water retention as well as the volume of the different pore size classes (e.g. biopores, macropores, mesopores, and micropores). For samples taken in 2016 soil water retention properties were determined using the evaporation method, which provided data points up to pF ca. 3.7 (varying with the samples). Around wilting point (pF 4.2) and beyond a dew point potentiometer provided additional measurement points. The associated software HYPROP-FIT (*Pertassek* et al. 2015) was used to initially merge the data from both sources, analyse it, and subsequently model the data to obtain fitted water retention curves. The model fits were used to determine averages of water retention curves per plot as shown in *Figure 8*. Around pF 1.5 to 2 and beyond pF 5 the retention properties in all plots were much alike. However, there was an issue with the fit between the water retention characteristic and total porosity as derived from bulk density. For a number of samples (15 of 42) the measurement started at pF 1 or even beyond, for the remainder the measurements started at pF 0. Particularly for these samples it presents the issue that in some cases the difference between water content at pF 0 and total porosity varied by up to 21 Vol-%. A reasonable difference between initial water content at saturation and total porosity is assumed to be around 5 Vol-%, which can be explained, e.g., by disconnected pore space remaining air-filled at saturation. For 20 of 42 samples the difference between total porosity and water content at saturation was larger than 5 Vol-% (mean 9±4 Vol-%, min 6 Vol-%, max 21 Vol-%). It is possible that samples were not fully saturated or quickly drained and that the HYPROP system nonetheless measured from matric potentials around pF0. Whether HYPROP and WP4C data fit well together can be used as an indicator of measurement accuracy, since both systems work separately, and for most samples the data from both sources showed good agreement (data not shown).

For samples taken in 2014, soil water retention was determined at several drainage levels, as can be seen in *Figure 9*. At the very first drainage steps, several samples lost some volume (2–4 mm). However, this was not previously accompanied by any swelling during saturation, the volume loss did not continue gradually while drying and there were no signs of lateral shrinkage (no detachment from the ring). Moreover, this behavior was observed mostly on samples from plot 6, containing a large amount of stones. Hence, a collapse in structure is likely the reason. Since preparing the site for planting new vines by breaking the ground open, the soil may not have self-organized itself to a stable condition. The newly prepared plot 6 and its adjacent spot 6a have distinctly different water retention curves; for plots 1–4 and the adjacent spot 1a they are considerably higher, due to a larger total porosity. Beyond pF 2 the water retention of spot 1a changes its curvature due to more rapidly decreasing, remaining water-filled pore volumes. A comparable, yet less pronounced behavior can also be seen for 6a.

The unmanaged site at the neighboring farm, Urikos, and the newly prepared plot 6, along with its adjacent spot 6a, have distinctly different water retention curves; for plots 1–4 and the adjacent spot 1a they are considerably higher, due to a larger total porosity. Beyond pF 2 the water retention of spot 1a changes its curvature due to more rapidly decreasing, remaining water-filled pore volumes. A comparable, yet less pronounced behavior can also be seen for 6a. The unmanaged sites Urikos and 6a as well as the newly ploughed plot 6 display similar water retention properties, while the unmanaged spot 1a shows similar properties as plots 1–4 roughly up to pF 2. Water retention curves can also be used to infer information about field capacity (FC, *Figs 8* and *9*) and wilting point (WP, *Fig. 8*). FC is often referred to at volumetric water contents at pF 2 or 2.5, where the larger pores are drained approximately within 2–3 days after a rain or irrigation event. WP is commonly set at pF 4.2 and refers to the water within the smallest pores as well as water films, beyond which plants begin to wilt. The difference between the two is the plant available water (PAW), which is held in the medium-sized pores and denotes the water which is not readily drained or held with too great forces in the soil matrix. FC and WP can be affected by different means, e.g. increase in OC by organic matter addition. For FC OC-induced changes in soil structure and decrease in bulk density by dilution with low-density OM may alter the water content at FC. For WP i.e. the additional large surface of OM may change the water content at WP. FC at pF 2 was fairly similar in 2016 between all plots ranging from ca. 29 to 34 Vol-%, in 2014 1–4 and 1a had a similar level (ca. 34 Vol-%), but 6, 6a and Urikos had lower FC (ca. 19 to 22 Vol-%). WP (only determined in 2016) ranged from ca. 7 to 13 Vol-% but since it was lowest for plots 1 and 5 (*Fig. 8*), drawing conclusions regarding the impact of management is difficult. In terms of soil structure, the water retention curves reveal that plot 5 has a similar ability to retain water as plots 0–4, however, at WP 5 retains very little water which may be linked to the lower OC content, providing less surface area for adsorption of water films. The similarly low WP of plot 1 cannot be explained in this context. Plot 6 has an overall lower available pore volume, leading to different water retention capacities, indicating the importance of soil structure. The soils' ability to store water in the range available to plants (PAW) is less relevant at Neuras, since the vineyards are irrigated. In 2014, managed plots display higher FC than unmanaged or recently ploughed plots. In 2016, unmanaged plot 5 has the largest PAW. Moreover, the dataset shows the differences in WP between the plots and it appears that long-term soil use had no clear effect on WP and hence on PAW evolution. There seems to be a trend of increased WP in managed plots. If increases at WP are larger than at FC, no net gain in PAW is achieved. Looking at *Figure 6* and *Table 4*, it becomes apparent that soil water content in 10 cm depth starts out wetter than at FC and does not quite reach WP, which means water stress would be modest. At lower depths (35, 58 and 108 cm) volumetric soil water content does not go below 0.2 cm^3/cm^3 (corresponds to 20 Vol-%), which means that roots and consequently vines in the top 1 m of soil are presumably not exposed to water deficit.

Despite the mutual irrigation schedule, plots 1–4 showed large variations in terms of surface soil moisture, both within and between plots (*Fig. 7*). This may partly be due to the uncontrolled amounts of water applied to each plot, 1 m^2 in one plot may receive a different amount of water than 1 m^2 in another plot. The within-plot variation may be related to the surface shape. As shown in *Figure 4*, the plots are not flat, so more water may be collected in local depressions. The plots displayed differences regarding water retention characteristics (*Fig.* 8), which is linked to total porosity and bulk density (*Table 1*). The differences between managed and unmanaged sites were even more obvious in the 2014 dataset. However, the rather small amount of samples does not provide a large enough basis for conclusions to be made. Nonetheless, trends can be discerned. The input of organic matter from decaying above- and belowground plant material of the vines likely improved soil structural development (e.g. *Eden* et al. 2017), manifesting itself in lower bulk densities and larger total porosities (*Table 2*) in plots 1–4, but also spot 1a, which may have benefited from plant roots extending beyond the plots. The lower bulk density and higher total porosity of plot 6 compared to spot 6a and Urikos may be related to the initial establishment of the vineyard in 2013, when the ground was rigged. This physical disruption may have artificially increased porosity.

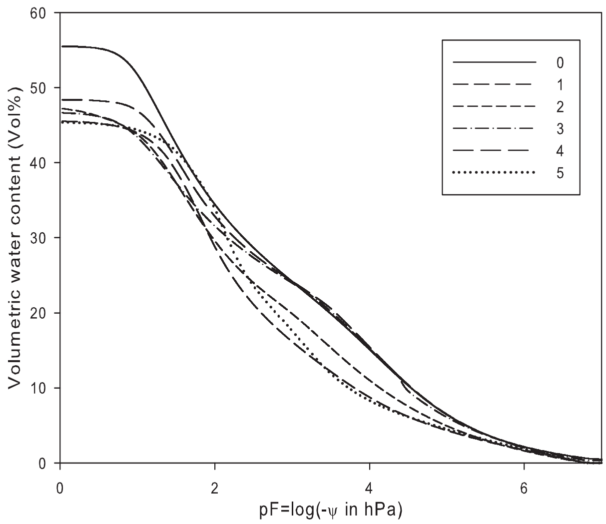

Fig. 8 *Modelled topsoil (ca. 5–10 cm depth) water retention curves for plots 0 to 5 based on data measured with HYPROP and WP4C. Model predictions are based on the PDI-variant of the bimodal unconstrained van Genuchten model and for two samples on the bimodal unconstrained van Genuchten-Mualem model (see text for details). Source: own drawing*

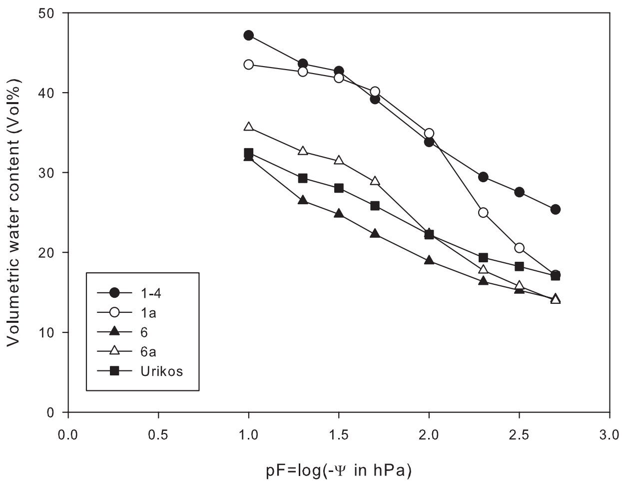

Fig. 9 *Volumetric water content of samples from 2014 as a function of pF at pF 1, 1.3, 1.5, 1.7, 2, 2.3, 2.5, 2.7. Source: own drawing*

Table 4 Field capacity (FC) at pF 2 and 2.5, wilting point (WP) and plant available water (PAW) using FC at pF 2 and 2.5, respectively of the sites in October 2016. Source: own measurements

2016	FC at pF 2 Vol-%	FC at pF 2.5 Vol-%	WP at pF 4.2 Vol-%	PAW 2 Vol-%	PAW 2.5 Vol-%
Plot 0	34.41±0.27	28.65±0.50	13.12±0.82	21.29±0.55	15.53±0.32
Plot 1	28.77±6.17	21.09±4.94	7.59±1.40	21.18±5.13	13.50±3.98
Plot 2	29.55±5.02	23.98±5.41	9.49±1.85	20.06±3.38	14.49±3.65
Plot 3	31.55±2.50	27.32±2.65	13.27±0.77	18.29±2.56	14.05±2.71
Plot 4	32.82±2.51	27.79±2.21	13.32±1.19	19.50±1.92	14.47±1.81
Plot 5	33.81±3.36	23.56±2.79	7.33±1.94	26.48±2.27	16.23±2.70

3.5 Impact of soil structure on vine and wine

In unirrigated field conditions, grape berry size is decreased and total phenolics are increased when vines face water deficits, which results in higher grape quality potential for red wine-making but lower yields; these effects were confirmed in irrigation trials (*van Leeuwen* and *Seguin* 2006). Only deficit irrigation can result in economically acceptable yields with high quality potential grapes in very dry regions; irrigation is likely to modify terroir expression (*van Leeuwen* and *Seguin* 2006). The ideal water status with regard to grape quality potential is highly dependent on yield: in dry farmed vineyards in dry areas, excellent red wines can be made from fruit grown on severely water stressed vines, as long as the yield is very low, whereas for higher yield, the best results in terms of quality are obtained when water deficit is mild, which might be achieved through deficit irrigation in dry areas (*van Leeuwen* and *Seguin* 2006). In this context, the flood irrigation applied in plots 1–4 is not suitable for deficit irrigation, whereas more control (and thus water deficit) is possible with the drip irrigation set-up in plot 6. Hence plot 6 may have a superior potential for higher quality grapes than plots 1–4. In the concept of terroir, fertilizer and even irrigation are external inputs (*Silbernagel* and *Hendrix* 2003). However, at Neuras grape production would not be possible without irrigation. Moreover, *Kool* et al. (2016) pointed out that irrigation is becoming increasingly common in viticulture.

The vine varieties in Neuras are grown in a warm climate and harvest is comparatively late. Under warm climatic conditions, late-ripening varieties are better suited, as quick ripening reduces aromatic expression in wine; grapes should just achieve ripeness under local climatic conditions (*van Leeuwen* and *Seguin* 2006). The varieties (*Table 5*) grown on plots 1–4 are early to late ripening (Shiraz, Merlot and Petit Verdot), while medium to very late ripening ones (Shiraz, Mourvedre and Grenache) are planted on plot 6. An internet search yielded various newspaper articles describing the quality of Neuras wines. The wine from the first harvest in 2001 turned out terrible (*Badenhop* 2016), but with the support of South African wine-makers the quality improved considerably in the following years. According to *Schier* (2009), Neuras Wines are produced to the South African standard, which is one of the most stringent in the world; samples are sent for testing there regularly. *New African Frontiers* (n.d.) provides a detailed description of both wines, Neuras Shiraz and Neuras Namib Red, where cultivars are not blended as wine but pressed together as grapes to enhance the fusion of the grapes. The vinery itself gives an overview of its products, including wine, dessert wine and brandy (*Neuras Vineyard* 2020).

Yield in 2017 was very low with just 2500 kg of grapes in total from plots 1–4 and 6, of which 1350 l wine and 150 l port were made. In comparison, the yield in 2015 from the older plots 1–4 alone was over 3550 kg of grapes producing more than 1850 l of brandy and port wine (1+4: 1224 kg → 695 l brandy; 2: 714 kg → 374 l port wine; 3: 1629 kg → 800 l brandy). On their homepage, the usual production is given with 3000 bottles per year (3000 bottles × 0.7 l are 2100 l) from the older plots, yield from the new plot is expected to increase production to 15,000 bottles (ca. 10,500 l) per year.

According to *van Leeuwen* and *Seguin* (2006), the zone most suited for growing high quality grapes is between 35° and 50° latitude, on both the northern and southern hemisphere, however, high altitude may compensate for low latitude. Neuras is located at 24°27′ S at an elevation of ca. 1225 m (*Fig. 4*), around harvest night temperatures are at 8–10 °C. Moreover, to achieve high quality red wines, moderate vine vigour can be induced by environmental conditions: moderate water deficit or low nitrogen supply (*van Leeuwen* and *Seguin* 2006). While the older plots receive ample amounts of water, the drip irrigation setup at plot 6 provides water in a more controllable way, hence vine vigour can be influenced. Vines receiving too much water may produce grapes, which are too large to be of high quality (*van Leeuwen* and *Seguin* 2006). This is the case in the old plots, the drip-irrigated vines produce higher quality grapes and hence wine

Table 5 Ripening phase, details on origin, and rank in the grape variety ranking of the vines grown at Neuras. Source: adopted from Tischelmayer (2018)

Grape variety	Prime name	Ripening phase	Details of origin
Shiraz	Syrah	Medium maturity	French variety, grown worldwide
Merlot		Early to medium	French variety, grown worldwide, first mentioned in 14th century
Petit Verdot		maturity	French variety, first mentioned in 1736
Mourvedre	Monastrell	Late maturity	Spanish variety, widespread, first mentioned in 1381
Grenache	Garnacha Tinta	Very late maturity	Spanish variety, first mentioned in 1513
Colombard		Late maturity	French variety, white, first mentioned in the early 18th century
Tannat		Medium maturity	French variety, first mentioned in 1783
Ruby Cabernet	Muscat à Petits Grains Rouges	Medium maturity	American variety, hybrid from UC Davis in 1936
Red Muscadel		Medium to late maturity	Greek variety (Maul et al. 2014)
Pinotage		Early to medium maturity	South African variety, hybrid from Stellenbosch University in 1924
Durif		Late maturity	French variety, mostly grown in California, first mentioned in 1868

(*Iván Phillipson,* personal communication, 10/2016). The ideal water status with regard to grape quality potential is highly dependent on yield: in dry farmed vineyards in dry areas, excellent red wines can be made from fruit grown on severely water stressed vines, as long as the yield is very low, whereas for higher yield, the best results in terms of quality are obtained when water deficit is mild, which might be achieved through deficit irrigation in dry areas (*van Leeuwen* and *Seguin* 2006). The flood irrigation applied in plots 1–4 is not suitable for deficit irrigation, whereas more control (and thus water deficit) is possible with the drip irrigation set-up in plot 6. Hence plot 6 may have a superior potential for higher quality grapes and wine than plots 1–4. Rough tasting grapes are consequently used to produce brandy.

Beyond the regular supply of water through irrigation the different soil structure in plots 1–4 vs. 6 is of relevance, as plot 6 has a far lower retention capacity for water (*Fig. 9*). This is linked to its bulk density and total porosity. Moreover, the soil structure is less stable (it presumably collapsed in several samples), as it was created during the establishment of the vineyard in 2013, when the ground was rigged. Rather than self-organization this physical disruption may have artificially increased porosity. Soil structural development in the older plots was likely driven over time by clay content and the input of organic matter from decaying above- and belowground plant material of the vines (e.g. *Eden* et al. 2017), manifesting itself in lower bulk densities and larger total porosities (*Table 2*) and an overall stable structure. The presence of organic carbon deriving from this source was shown with the $\delta^{13}C$ measurements. This clearly shows the impact of management on soil structure and its evolution.

4. Conclusions

The soil structure at Neuras has been altered by the practices applied on the long-term managed plots. Bulk density tends to be lower on plots 0–4 than on reference plot 5, the newly established plot 6, and the nearby shrubland at Urikos. In the 2014 dataset, these changes were visible for total porosity. Total carbon, calcite, organic carbon, and total nitrogen were also higher in managed plots in 2014; $\delta^{13}C$ was lower. In 2016, the reference plot 5 was in general more similar to the plots 0–4, which may be related to its location within the same depression, this indicates the impact of the geomorphological setting. However, as visible for Urikos in 2014, EC and CEC displayed clearer differences with the managed plots. Clay mineralogy was also affected in managed soils.

Particularly the irrigation causes changes to soil hydraulic properties, as can be seen from *Figure 6.* A non-irrigated soil would dry out and maintain low moisture levels until water infiltrates during a rain event. Nonetheless, field moisture conditions vary greatly within and between plots (*Fig. 7*). The ability to hold moisture has changed in the managed plots, likely due to irrigation – leading to swelling and shrinkage of clay minerals – and input of organic material of vine plants, as indicated by the altered bulk densities and total porosities, and water retention curves. The impact of soil management thus affected the evolution of soil structure. Beyond this impact though also location, within a depression or on slightly-sloping land is of importance, e.g. regarding the infiltration of surface water (or its runoff) as well as the underlying material for pedogenesis. The fact that surface soil moisture could not be determined on plot 5 though shows the difference in soil structural development of managed plots 1–4 in an otherwise similar setting (geology, geomorphology).

The unique conditions found at Neuras are strongly related to its location near the Namib Desert with its extreme climatic conditions; however, soil use and management have altered soil structure and properties. Overall, it is particularly important to determine the goal of land management, which in this case is the question of quantity or quality, which in turn affects the choice of irrigation method. On the other hand, experiences made here cannot easily be transferred to other localities as the environmental conditions are rather unique.

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