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Soil quality index for assessing phosphate mining restoration in a hyper-arid environment

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ABSTRACT

Mining contributes significantly to economic development, but it also entails extensive environmental damage, such as soil degradation and water and air pollution. Mining activity impacts the soil quality, often making it unable to support ecosystem function and structure. The current study aims to apply the soil quality index (SQI) as a methodology for quantifying soil restoration status in an open-pit phosphate mine in Israel's hyper-arid environment. In this regard, we evaluated an ecological restoration practice that includes topsoil refilling compared to the adjacent undisturbed natural system, using transformed and standardized scorings of 11 physical, biological, and chemical soil properties that were further statistically integrated into overall SQI values. Our results revealed significant differences between the restoration practice areas and the nearby natural areas, with a higher soil quality value in the latter. It is proposed that the topsoil restoration method is mainly affected by soil biological indicators, such as soil organic matter, soil proteins, and polysaccharides related to micro-organic growth, and in a lesser extent, by physical properties (primarily infiltration rate, followed by AWC). The former properties encourage the biocrust establishment, which is essential for soil surface stabilization and affects the water infiltration rate and nutrient availability. The chemical indicators showed no significant differences between most of the sites for the overall soil quality. In conclusion, soil properties, primarily physio-biological ones, should be selected to quantify and evaluate restoration practices in hyper-arid ecosystems.

1. Introduction

Mining contributes significantly to economic development at both the local and global levels. However, these contributions are frequently accompanied by extensive environmental damage, such as widespread land degradation, water, and air pollution, and other environmental disturbances (Feng et al., 2019). Mining entails the removal of vegetation, soil seed-banks, and topsoil layers, which alters the landscape, changing surface and subsurface hydrology, and causing soil quality deterioration (Martins et al., 2020). Therefore, the ecological restoration of mining areas presents a significant challenge (Zou, 2019). Mining restoration can be applied in three main techniques: (1) reclamation aims to stabilize the land surface and to return the surface to its original topography, mainly as an aesthetic improvement and to ensure public safety; (2) rehabilitation intends to transform the land into a different state than the original one by repairing the impact of mining and improving land productivity (Aronson et al., 1993; Mensah, 2015); and (3) restoration that seeks to return the land to its original function and conditions, thus restoring the ecosystem that was degraded or damaged to its previous state (Maiti, 2012). Although full recovery of the ecosystem function and structure is almost impossible in the short run, the recovery processes can be examined by selecting pre-defined indicators to evaluate restoration success (Bradshaw, 1997). The massive damage caused by mining has led many countries to establish restoration and rehabilitation policies (Maiti and Ahirwal, 2019). Therefore, selecting reliable indicators to assess restoration success is necessary for

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determining policy and decision making.

Restoration processes include two types of practices: active and passive. The active-type procedures are based on human intervention, such as topsoil and seedling application and plantation. The passive type is established upon natural regeneration processes (Bandyopadhyay and Maiti, 2019). Many studies have proposed various indicators to evaluate mining restoration (Bandyopadhyay and Maiti, 2019; Borges et al., 2019; Toktar et al., 2016; Wang et al., 2018). These indicators are divided into six groups, including soil quality assessment, enzymatic activity, litter accumulation and decomposition, plant cover and species composition, faunal communities, microbial communities, and biomarkers (Bandyopadhyay and Maiti, 2019). One of the means for assessing mining restoration is by using the soil quality assessment approach. Soil quality, which considers several physical, biological, and chemical soil properties, refers to the soil's capacity to sustain and support its health and productivity within the related ecosystem (Karlen et al., 1997; Lal, 2011). Assessment of soil quality is often discussed in the context of agricultural activities (Doran and Zeiss, 2000; Lal, 2015), whereas less attention has been given to other practices, such as mining (Borůvka et al., 2012; Menta et al., 2014; Muñoz-Rojas, 2018). Therefore, defining soil quality indicators by selecting soil properties for evaluating restoration practices that include adding topsoil is an essential step in determining their success.

The soil quality index (SQI) is a diagnostic procedure to evaluate soil function and overall health. The SQI usually integrates physical, biological, and chemical properties into a single weighted number (Bastida et al., 2008). The selected soil properties need to be relevant to soil processes, consistent, reproducible, and relatively easy and affordable to sample (Bünemann et al., 2018; Moebius-Clune, 2017). The physical properties examined for the restoration success assessment are related to soil structure, and include texture, bulk density, water holding capacity, infiltration rate, penetration resistance, available water content, and aggregate stability (Bandyopadhyay and Maiti, 2019). Biological properties refer to macro- and micro-organisms in the soil, such as microbial biomass, respiration, community composition, and enzymatic activity (Muñoz-Rojas, 2018), as well as processes related to soil organic matter and active carbon (Sheoran et al., 2010). The soil chemical properties include pH, salinity, nutrient availability (e.g., ammonium (NH_4^+), nitrite (NO_3^-), phosphorus (P), and potassium (K)), cation-exchange capacity, nutrient cycling, and heavy metals content (Dunger and Voigtländer, 2005; Gómez-Sagasti et al., 2012; Melgar-Ramírez et al., 2012; Sheoran et al., 2010). The physical, biological, and chemical soil properties are interlinked, affecting biocrust and vegetation regeneration and growth. For example, low pH increases the solubility of naturally occurring micro-nutrients (e.g., Fe, Mn, Cu) to toxic levels, limiting most plants' growth in mining areas (Wong, 2003). Therefore, a holistic approach for assessing soil quality is a valuable asset in evaluating restoration success in mining areas.

Each soil property should be carefully considered to avoid time-consuming and costly efforts while enabling an adequate restoration success assessment. Thus, the first step in developing an SQI is selecting the most suitable and relevant properties and creating a minimal dataset that best represents the soil characteristics and management practices (Asensio et al., 2013a; Karlen et al., 2003; Puglisi et al., 2006). Once the minimal dataset is established, each soil property is then transformed into unitless scores, allowing the grouping of the selected properties to produce a single scaled value ranging from 0 to 1 (Andrews et al., 2002; Karlen et al., 2003). The SQI is then weighted by a PCA and/or summarized to calculate the overall SQI. The uses of SQIs are varied, and they are applied to assess agricultural, natural, and polluted soils (e.g., Armenise et al., 2013; Beniston et al., 2016; Karlen et al., 2003; Levi et al., 2020; Masto et al., 2008a, 2008b; Paz-Kagan et al., 2015). Less frequently, these indices have been applied to determine management effects on restoration success in open-pit mines (Asensio et al., 2013a, 2013b; Mukhopadhyay et al., 2014; Pietrzykowski, 2014). Moreover, although the SQI has proved to be a highly reliable approach, it has seldom been applied in arid environments (Blecker et al., 2012). Since arid soils are often alkaline and highly saline, have a low nutrient and organic matter content, and are generally more erodible (Mendez and Maier, 2008), restoration of degraded soil is a slow and complicated process (Yirdaw et al., 2017). All these characteristics highlight the challenges in the recovery of degraded mining areas in hyper-arid environments and the need to select appropriate soil properties to determine the overall SQI.

The present study strives to evaluate the effects of restoration practices (i.e., topsoil restoration) on soil quality properties compared to adjacent natural areas in an open-pit phosphate mine in a hyper-arid region of Israel. It should be noted that the topsoil mostly contains soil organic matter (SOM), nutrients, and plant seed banks (Borůvka et al., 2012), and is the habitat of soil micro-biota, all supporting the overall soil restoration (Bowker et al., 2005; Visser et al., 1984). Therefore, it has been shown that using topsoil as an amendment improves the physical, biological, and chemical properties for ecological soil restoration in mines (McGinnies and Nicholas, 1980; Mensah, 2015; Sheoran et al., 2010; Visser et al., 1984). Accordingly, our first goal was to find out whether an area to which the topsoil conservation method was applied resembles the adjacent natural area in terms of soil properties and overall soil quality, despite the extreme environmental and climatic conditions in this hyper-arid region. Our second goal was to evaluate the restoration success based on the SQI approach as a function of time by comparing the different restoration stages applied in various sites. Therefore, the hypothesis is that the topsoil method in mines would enhance overall SQI and restoration efforts, where the timespan since restoration would also affect the emerging processes due to the poor, slow soil development in such a hyper-arid environment.

2. Methods

2.1. Study area and mining restoration practices

The study took place in an open-pit phosphate mine in the Negev Desert, Israel. The Zin phosphate mine includes 30.4 km^2 that have been mined over the last four decades (Fig. 1). It is one of several mining fields located at the eastern edge of the Negev Highlands. The local climate is hyper-arid with a long-term annual average rainfall of about 50 mm and high potential evapotranspiration rates. The long-term monthly average temperature is 26 °C during the summer months of July and August, and 10 °C during the winter month of January (Israel Meteorological Service, IMS). The geology of the study area is characterized by a sequence of the northeast to southwest trending synclines and anticlines formed during the Upper Cretaceous geological period, about 72–84 MYA. Flooding of the area in geological times resulted in the deposition of marine sediments, reflecting high productivity (Soudry, 1992). The phosphate deposits are layered within sequences of charts, chalk carbonates, and limestone, located mainly at the northern edge of the synclines (Nathan et al., 1997). The rich phosphate deposit comprises approximately 2–6 layers (0.5–1.5 m thickness), mixed with other (low-level) phosphate layers that are not relevant for mining. The phosphate deposit rock is from the same geological period and is part of the Mediterranean phosphate belt that extends from Turkey through Jordan to Israel.

The Zin mining site has been active since the 1970s and is the largest of its kind in Israel. Until the 1990s, minimal efforts were made to rehabilitate the area. These efforts mainly included redistributing the overburden into the open pit and stabilizing the surface using road rollers to return it to its original topography and were prevalent until the beginning of the 1990s. However, for the past 20 years, the mining practices have changed towards a more ecological restoration approach that includes topsoil applications with the following steps. First, topsoil (upper 50 cm) is removed and kept separately. According to the original topography, the overburden is then returned to the open pit after mining and rearranged into a predetermined geo-morphological design. Finally,

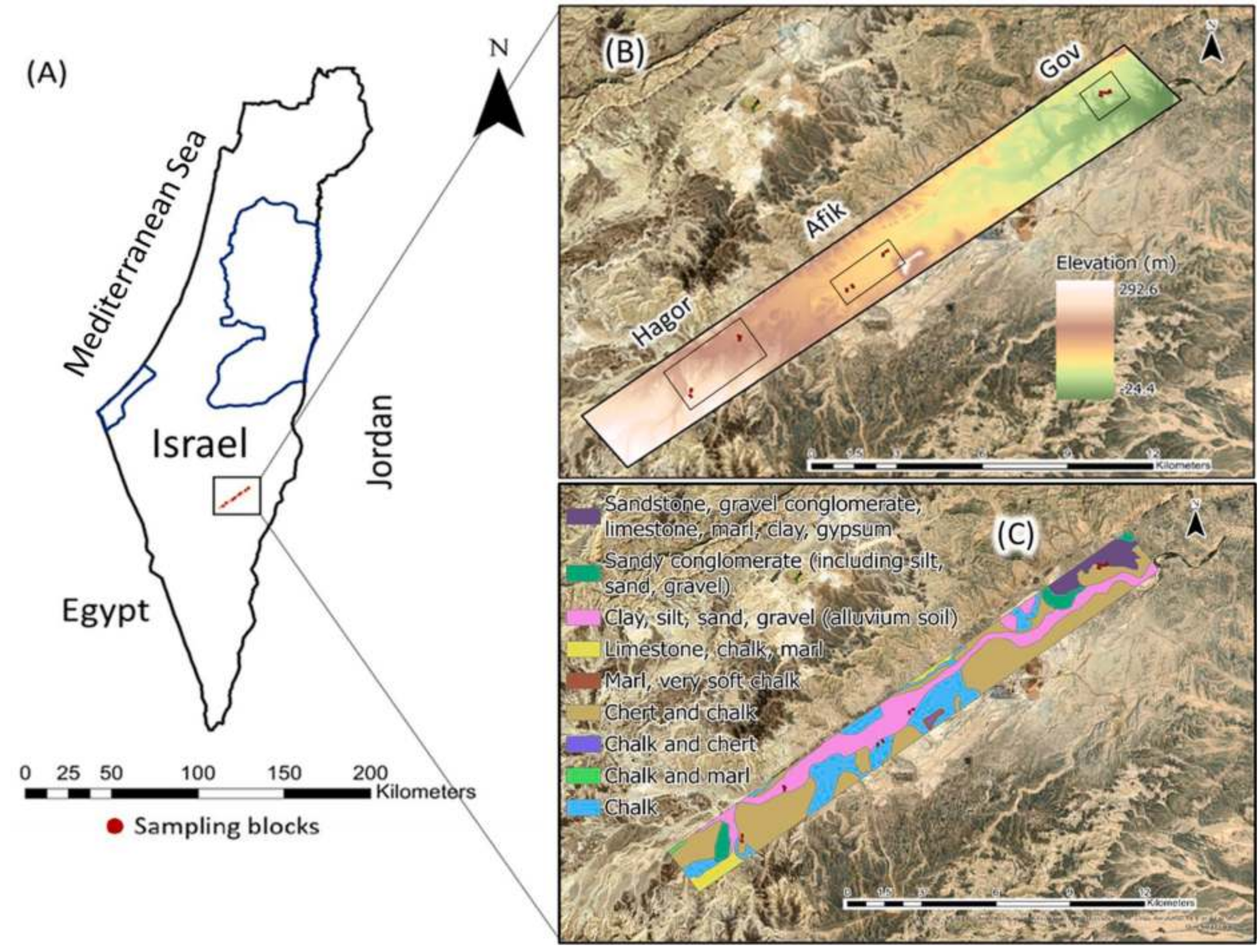


Fig. 1. Schematic map with the location of the Zin phosphate mining field (A); Zin mining field topographic (B); and geological map; (C) with the sampling blocks of the three study sites of Gov, Afik, and Hagor (red points). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the topsoil that was removed from an adjacent open-pit mining area is placed over the fill material and turned over to increase the large stone cover. This method enables a rapid placement of the topsoil rather than piling it up over time (Ghose, 2004). The restored site is returned to its original topography and is designed to slow runoff to create micro-climate conditions and diverse habitats, to enhance efforts to restore the soil micro-organisms, seed banks, and biocrusts. The applied restoration practice has a substantial impact on soil quality indicators, as seen in various sites at different timespans since restoration (Menta et al., 2014). In this study, three restoration sites of three different time periods since restoration were evaluated and compared to their adjacent natural areas, based on the SQI approach.

2.2. Soil sampling design

Three restoration sites at the Zin open-pit phosphate mines were chosen for the study, representing both temporal and spatial variations. The restoration sites include the Gov, Hagor, and Afik sites. These sites were restored at different periods, in 2007, 2010, and 2014, respectively. Soil sampling in all sites took place during April 2017. The experimental design includes two pre-designated plots of 50 × 100 m, divided into 100-m^2 grid cells. To compare the restored sites with the adjacent natural area, we selected a nearby undisturbed natural site. Two additional pre-designated plots of 50 × 100 m divided into 100-m^2 grid cells were established (Fig. 1). Five soil samples were collected from the four corners and the center of the grid cells in each plot for each block, resulting in a total number of 60 soil samples of 30 restored and 30 natural samples, classified by their respective restoration site. For each of the soil samples, 15 soil properties were selected to evaluate the overall SQI. Samples were collected in paper bags from a depth of up to 20 cm and transferred to the laboratory for wet chemistry analysis. Therefore, the soil samples represent only the upper layer of the topsoil to evaluate the restoration processes and biocrust development in this hyper-arid region. In addition, samples for biocrust analysis were collected in 64-cm^2 Petri-dishes. Penetration and infiltration rates were measured in the field for all soil samples.

2.3. Selecting soil properties

Overall, 15 soil properties were selected due to their relevance to mining restoration success. These were divided into physical, chemical, and biological properties. Table 1 shows the selected properties and their importance for the soil quality assessment in evaluating restoration success. The physical properties include soil texture (sand, silt, and clay fraction) for determining water storage and the infiltration rate. The available water content (AWC) was used to assess water availability in the soil, water storage capacity, and drought resistance. AWC is the difference between water stored in a field capacity and at the wilting point (Schindelbeck et al., 2008). The infiltration rate indicates hydrological processes, such as runoff, infiltration, and soil moisture. Dryland soils support rich microphytic communities that are critically important for developing and establishing biocrust cover, which regulates water delivery and retention, reduces surface ponding, inhibits runoff and sediment production, and improves moisture storage (Eldridge et al.,

Table 1
Soil properties for soil quality assessment in open-pit phosphate mines, their functions, their laboratory chemical analysis methods, and their measurement units.

Indicator	Reason for selection	Unit	Method
Physical			
Soil texture (sand, silt, and clay)	Related to SOM levels, defines water storage in the soil and infiltration rate	%	Particle size suspension
Available water content (AWC)	Explains potential soil water availability, plant available water storage capacity, and drought resistance	%	Oven drying
Infiltration rate	Explains potential runoff, soil erosion and leaching, soil porosity, and compaction	cm/sec	Mini-disc infiltrometer Madsen and Chandler (2007)
Chemical			
pH	Influences plant growth, toxicities, and metals availability. Affecting the available macro and micro-nutrients		Water-soil suspension
Electrical conductivity	Defines soil salinity, affecting plant growth	dS/m	Water-soil suspension
Cl	Defines soil salinity, affecting plant growth	mg/L	
Na	Defines soil salinity, affecting plant growth	mg/L	
Ca + Mg	Defines soil salinity, affecting plant growth	mg/L	
N-NO_3	N containing life-building blocks, N release	mg/kg	ICP-MS
N-NH_4	N containing life-building blocks, N release	mg/kg	
Phosphorus (P)	Influences plant productivity, helps in mineralization of SOM, vital nutrients to plant development	mg/kg	
Potassium (K)	Influences plant productivity, helps in mineralization of SOM, vital nutrients to plant development	mg/kg	
Biological			
Soil organic matter	Source of nitrogen, phosphorus, and sulfur, improves aggregation and infiltration, increases water and nutrient availability	%	Organic carbon furnace method Schulte (1995)
Protein	Microbial abundance and activity and development of soil biological crust	mg/g	Lowry method, 0.1 N NaOH Lowry et al. (1951)
Polysaccharides	Microbial abundance and activity and development of soil biological crust	mg/g	Anthron, sulfuric acid Dische (1955)

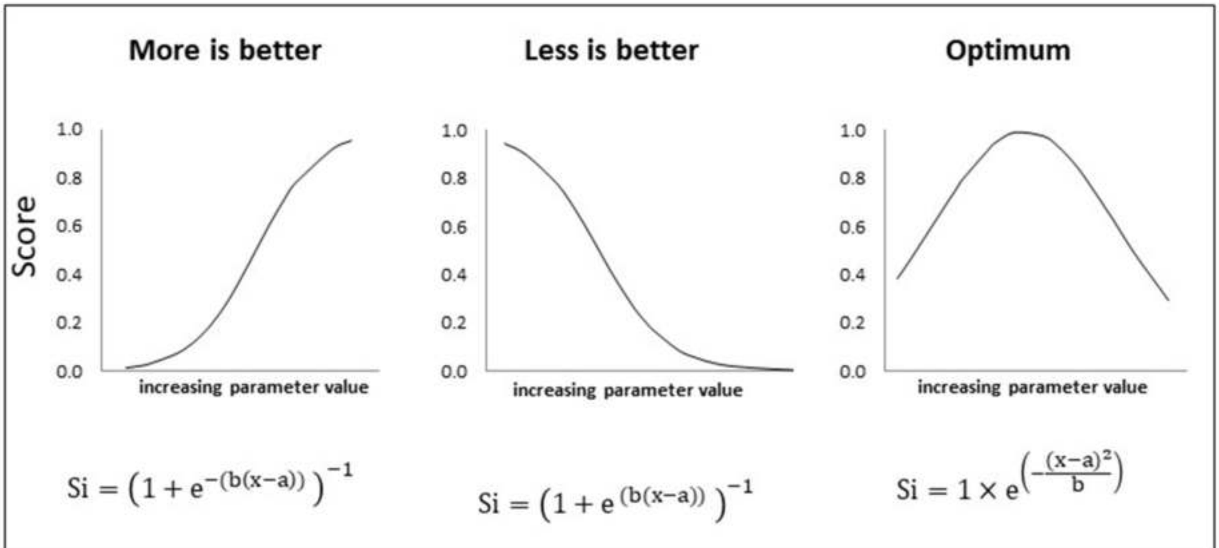
2020). Yet, biocrust are also clearly physical features of the soil, given that the component organisms are in direct content with the upper soil surface layer (Bowker et al., 2018). Thus, biocrusts development regulates hydrological processes and plays an essential role as ecosystem engineers (Jones et al., 1997), enhancing ecosystem quality in a hyper-arid context. The biological properties include soil organic matter (SOM), related to nutrient storage, and water availability in the soil. Soil protein and polysaccharides are related to micro-organisms and biocrust development. The chemical soil properties include pH, electrical conductivity (EC), and its derivatives, comprising sodium (Na), calcium and magnesium (Ca + Mg), and chlorine (Cl), which are related to soil salinization and salt content. Also, phosphorus (P), potassium (K), nitrate (N-NO_3^-), and ammonium (N-NH_4^+) were extracted. These elements are related to nutrient content and use efficiency, which are necessary components for plant regeneration, growth, and health.

Table 1 depicts the selected soil properties and the analytical method applied for their analysis in the laboratory. Soil texture refers to a mixture of mineral particle sizes and the fraction of sand, silt, and clay in the evaluated soil, based on Schindelbeck et al. (2008). Thus, soil texture is not part of the SQI since it is a relatively constant and mostly descriptive parameter (Karlen et al., 2003). However, soil texture is essential to interpret most soil properties in the SQI. Available water content (AWC) was measured by calculating the differences between saturated soil (i.e., water content at field capacity) and the permanent wilting point based on soil physical and hydraulic properties according to soil texture (Farrick et al., 2019). The infiltration rate was measured in-situ using a mini-disk infiltrometer (Madsen and Chandler, 2007). Soil organic matter (SOM) was measured by oven-drying the soil samples for 3 h at 105 °C, followed by burning the soil at 500 °C for another 2 h and weighing the soil samples before and after burning (Casida et al., 1964). Potassium chloride extractions were measured to evaluate the extractable nitrate (NO_3^-) and ammonium (NH_4^+) content (Drinkwater et al., 2015). Soil proteins were measured by the Lowry method, extracted by 0.1 N NaOH (Lowry et al., 1951), and polysaccharides were measured by sulfuric acid extraction. Soil nutrients (P, K, Na, Ca, Mg) were analyzed by inductively coupled plasma mass spectrometry (ICP-MS), using an ammonium acetate and acetic acid solution (Brady and Weil, 1999). The pH values were determined by using a pH electrode probe. Finally, EC was measured using an EC meter on well-stirred soil.

2.4. Soil quality index development

SQI development involves several statistical steps. The first step is to transform all properties into unitless scores ranging from 0 to 1. This process is necessary to standardize each soil property so they will have comparable units. However, before applying the transformation functions (Fig. 2), outlier detection and removal and missing data completion based on a regression imputation was applied (Dumedah and Coulibaly, 2011). The median absolute deviation (MAD) approach for removing a minimum number of outliers to exclude only the most extreme values was used. Thus, only outliers that were either higher or lower than three standard deviations around the median value were removed (Levi et al., 2020; Leys et al., 2013), resulting in a < 5% reduction for each soil property. The second step involves calculating the SQI (Andrews et al., 2002; Paz-Kagan et al., 2015; Rezaei et al., 2006; Sharma et al., 2005). This step was performed by assigning one of three scoring functions to each indicator according to its performance and based on previous literature (Fig. 2; Karlen et al., 2003; Masto et al., 2008a, 2008b; Mukhopadhyay et al., 2014). To exclude highly correlated indicators from the SQI analysis, Wetschoreck et al. (2020) developed the predictive power score (PPS) method that normalizes the various pairwise relationships to their local baseline (values range from 0 to 1), both linear and non-linear correlations of higher dimensions, and also presumes asymmetry, where the two halves of the prediction matrix account for the direction of the relationship (i.e., $X \sim Y \neq Y \sim X$). Pairs of predicted scores with PPS $\geq$ 0.5 were excluded. The PPS calculation scheme was imported from python into R (Zavarella, 2020), using the “reticulate” package (Ushey et al., 2020).

The second step involves calculating the SQI (Andrews et al., 2002; Paz-Kagan et al., 2015; Rezaei et al., 2006; Sharma et al., 2005). The SQI calculation is based on a principal component analysis (PCA) on the scored data. The variance of the data is binned into statistically distinct low-covariable classes, named principal components (PCs), where each PC accounts for a portion of the model’s variance, and the minimal number of the most explanatory PCs is selected to reduce the dimension and complexity of the model (Jolliffe et al., 2016). A PCA was calculated for all restoration sites combined and also for each separately. PCs with eigenvalues (i.e., weighted proportion of variance) greater than 1 and that also explain more than 5% of the model’s variation were included in the model. The highest loadings, defined as having an absolute value within 10% of the highest factor loading for the soil indicators, were used to indicate the most influential PC on each soil property (Masto



More is better	Less is better	Optimum
Soil organic matter (SOM)	Electrical conductivity (EC)	pH
Protein	Infiltration	NH_4^+
Polysaccharides		NO_3^-
Available water content (AWC)		P
		K

Fig. 2. Scoring functions for data standardization, assigning the appropriate term and function to each soil property. Si is the soil property score, x is the parameter value, a is the soil property average, and b is $2\sigma^{-2}$ of the data. The graphs are adapted from Karlen et al. (2003). AWC: available water content, SOM: soil organic matter, EC: electrical conductivity, K: potassium, and P: phosphorus.

et al., 2008a, 2008b). However, the contrast among PCs for highest loadings wasn't distinct enough for some soil properties, which might create ambiguous and arbitrary factor loadings rather than a significant relationship in the correlation matrix. Therefore, a varimax rotation PCA was applied to the results of the initial PCA (Kaiser, 1958). The rotation of the projected correlations enhances the variations, maximizes the contrasts among the selected amount of PCs, and maintains the total cumulative proportion of variance. The third step includes the final SQI calculation by dividing the proportion of each rotated principal component variance by the cumulative variance to generate the weights, which are then multiplied by the number of the highest correlated variables related to each rotated PC (Masto et al., 2008a, 2008b). Each indicator is then multiplied by its corresponding weight to calculate the overall SQI (Eq. (1)). The scored values were multiplied with their weighted values for calculating the soil quality index (SQI):

$$SQI = \sum_{i=1}^{n} PWi \times Si' \quad (1)$$

where *PWi* is the PCA weighting factor, and *Si'* is the scoring function's ranks of each soil property, indexed as *i*, and *n* is the total number of properties.

2.5. Statistical analysis

Once the scores and the SQI were calculated, the differences were tested for their significance between the treatments (natural vs. restored) for each soil property in each site and between sites, as well as for the overall SQIs and their respective physical, biological, and chemical components. The sampling pattern includes spatially various sites that subsume multiple self-dependent plots with low variances within each. Therefore, the mixed-effects nested design analysis of variance (ANOVA) model (Schielzeth and Nakagawa, 2013) was used to examine significant differences, where sites and treatments were determined as fixed factors and the nested plots were defined as random. The ANOVA was first used to explore the overall success of the ecological restorations and their adjacent natural areas. Second, to measure differences between the individual study sites for each group of indicators-physical, biological, and chemical-and overall SQI scores. The basic assumptions of the ANOVA for normal distribution of the model's residuals and homoscedasticity of the scored properties were tested. The residual distribution histogram results of the mixed-effect ANOVA tests for the individual scored soil indicators are shown in Appendix 1. For properties that had their assumptions unmet ($p < 0.05$), a non-parametric rank-transformation approach was used, where the scored values were gradually rated from lowest to highest scores (Conover and Iman, 1981), and were then compared using the nested ANOVA test. Multiple comparisons among all factor levels were calculated using the Tukey HSD test. The level of significance for the soil indicators and SQI was determined at $\alpha < 0.05$. The regular and the varimax rotation PCA, and the nested design ANOVA tests were performed using JMP® Pro-software version 15.0.0 (SAS Institute Inc., Cary, NC, USA).

3. Results

3.1. Soil quality indicators

The results of the predictive power score (PPS) matrix for the scored soil properties show that Cl and Na were highly correlated with EC ($PPS_{(cl \rightarrow EC)} = 0.7$ and $PPS_{(Na \rightarrow EC)} = 0.68$, respectively) and with each other. Although Mg + Ca correlation with EC was lower than 0.5 ($PPS_{(cl \rightarrow EC)} = 0.48$), due to its relatively close value, it was joined with Cl and Na to be excluded from further discussion to prevent collinearity and redundancy in the SQI model (Fig. 3). Also, relatively strong correlations were found for NO_3 and EC ($PPS_{(NO3 \rightarrow EC)} = 0.4$) and Cl ($PPS_{(NO3 \rightarrow Cl)} = 0.34$), but eventually, it remained in the SQI calculation model. In total, four out of the initial 15 properties were omitted from the SQI development, including the Cl, Na, and Ca + Mg that were highly correlated to EC and represent salinity indicators. The soil texture was also not part of the SQI since it is a relatively constant and mostly descriptive parameter, so soil texture and its fractions were not included in the SQI calculation. Table 2 displays the results of the significant differences found for the scored soil properties in the nested ANOVA for the individual and combined restoration sites (i.e., Gov, Hagor, and Afik) compared to their adjacent natural areas. Most scored indicators were eligible for the nested ANOVA test using their scored values, whereas five were tested based on their ranked-transformed values, including pH, $N\text{-}NH_4^+$, $N\text{-}NO_3^-$, K, and proteins, as their basic assumption for normal distribution of the model's residuals was unmet (Appendix A). The number of significantly different soil properties was reduced in response to the time since restoration. SOM was the only parameter to be consistently significant for all sites, and infiltration was significantly different at the younger Hagor and Afik sites. When comparing all restored plots and their natural counterparts, significant differences were found for four out of 11 indicators, including infiltration, SOM,

Table 2
Significant differences (p-values) between sites' restoration and their adjacent natural areas. Bold values are statistically significant ($\alpha < 0.05$).

Soil properties	Gov natural vs. restoration	Hagor natural vs. restoration	Afik natural vs. restoration	All-natural vs. restoration
AWC	0.988	0.766	0.424	0.963
Infiltration	0.848	**0.002**	**0.005**	**0.005**
pH	0.518	0.888	0.994	0.481
EC	0.837	0.868	0.986	0.748
$N\text{-}NH_4$	0.487	0.999	**0.017**	0.125
$N\text{-}NO_3$	**0.029**	0.985	0.984	0.548
P	0.779	**0.043**	0.994	**0.024**
K	0.245	0.763	0.275	0.442
SOM	**0.037**	**0.000**	**0.000**	**0.000**
Protein	0.252	0.691	0.818	0.314
Polysaccharides	0.694	0.611	**0.008**	**0.033**
Significant	**2**	**3**	**4**	**4**

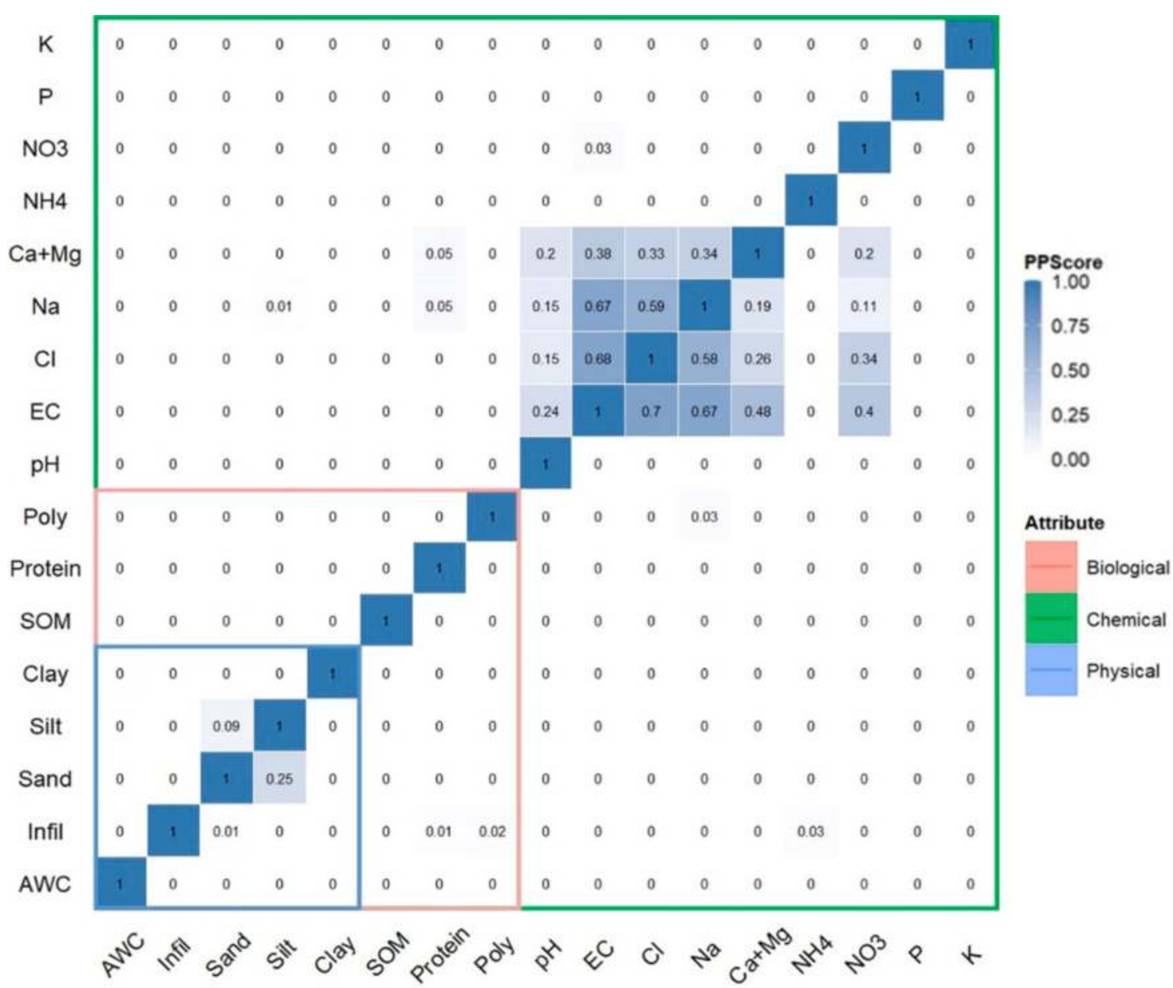


Fig. 3. Predictive power score (PPS) matrix results for all the scored soil properties. Darker shades of blue represent stronger correlations between each pair of variables. The colored frames represent the associated physical, biological, and chemical components of the soil properties. SQI: soil quality index, AWC: available water content, SOM: soil organic matter, EC: electrical conductivity, K: potassium, P: phosphorus, and Poly: polysaccharides. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

polysaccharides, and P.

Fig. 4 presents the box-whisker plot of all scored soil indicators, comparing each study site with its adjacent natural area. The spatial variability has no consistent increasing or decreasing pattern between the different sites and the time since restoration. The restored and related natural plots also displayed different trends within the study sites, mainly in the Afik study site. Despite being the most recently restored, the AWC, SOM, protein, and polysaccharide indicators showed generally higher scores than those of Hagor and Gov. In most cases, two study sites-Gov and Hagor-exhibited similar trends to each other with regard to their natural sites. The Hagor site presented a unique trend of slightly, yet not significantly, higher scores in the restored plots for some of the indicators, including AWC, proteins, and polysaccharides. The SOM indicator differences was significant in all study sites, showing a similar trend in comparing restoration sites and their adjacent natural sites, with a higher SOM value in the natural sites. A high infiltration rate was found in all restored sites, with lower scores than their natural counterparts.

3.2. Soil quality index

Fig. 5 shows spider diagrams that demonstrate the differences between the natural and restored plots. Values are given in unitless scores ranging from 0 to 1, based on the transformed properties' mean values. A combination of all sites shows noticeable differences in the physical, chemical, and biological soil properties. When observing the study sites separately, varying patterns emerge. In the Hagor and Afik sites, there is a clear difference between the spider patterns for each treatment, whereas, at the Gov site, the scoring values are relatively similar for most soil properties. Performing the PCA and applying the weights on the scored data translated the values into SQI scores, which allowed to compare the topsoil restoration treatment with the natural soils relative to one another.

Based on the transformed physical, biological, and chemical data using the three scoring functions (Fig. 2), the SQI was developed (Eq. (1)). The SQI model was applied for each site separately and all sites together. The PCA for all sites combined showed that four PCs had eigenvalues greater than one and had a greater proportion of variance

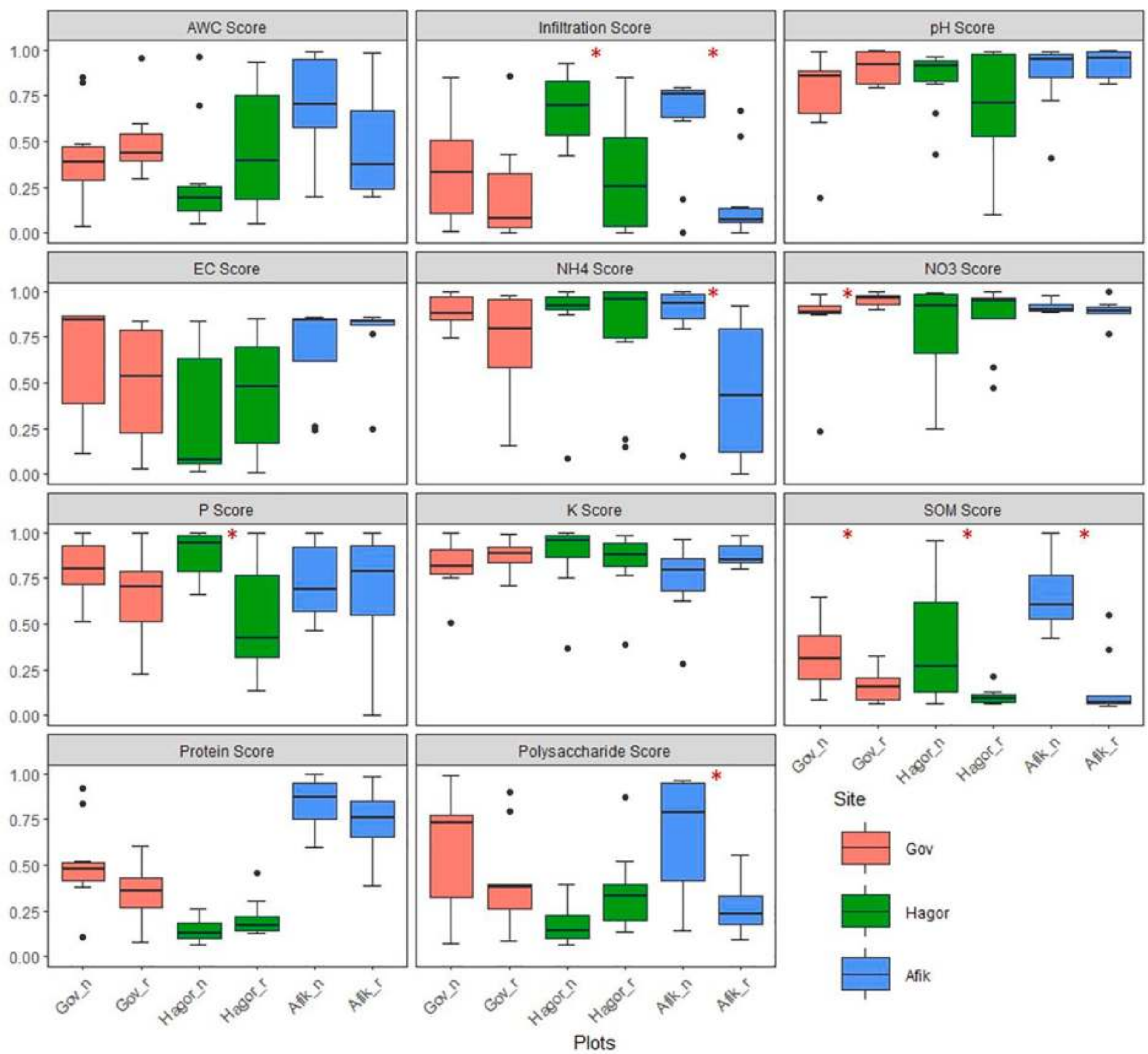


Fig. 4. Box-whisker plot showing the value distributions and outliers of each of the soil properties in the natural and restored study sites. Red asterisks represent significant differences ($p < 0.05$) between treatments within sites. AWC: available water content, SOM: soil organic matter, EC: electrical conductivity, K: potassium, and P: phosphorus; n refers to the natural area, and r refers to restored. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

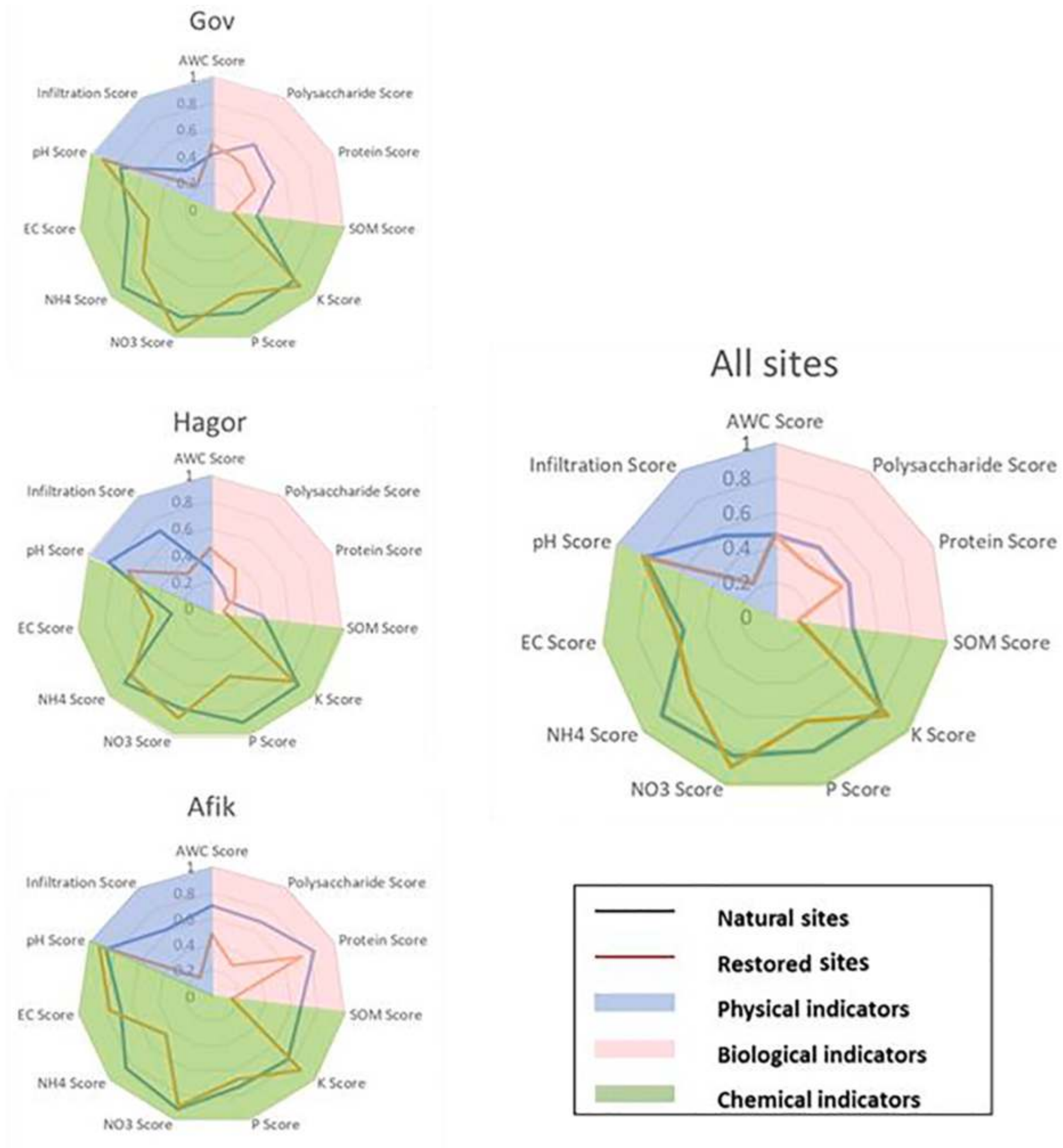


Fig. 5. Spider diagrams showing the differences between the natural and restored plots in unitless scores. AWC: available water content, SOM: soil organic matter, EC: electrical conductivity, K: potassium, and P: phosphorus.

than 5%. However, PC5 had a very close eigenvalue of 0.993. Therefore, it was incorporated into the accounted PCs, which eventually explained 68.1% of the total cumulative variance. The respective enhanced varimax rotated factor loadings for the five PCs are presented in Table 3. The PCA models showed that Gov had three, Hagor had five, and Afik had three PCs that met the two conditions, respectively. The models had an overall cumulative variance for the Gov, Hagor, and Afik sites of 65.9, 77.5, and 67.2%, respectively. The detailed varimax rotation PCA results for each site separately are shown in Appendix B.

Fig. 6 presents the integration of the physical, biological, and chemical scores and the overall SQI for all three sites, independently and combined. The results reveal the significant differences between Gov, Afik, and all sites between natural and restored sites. The mean SQI scores for all sites combined were higher in the natural than in the restored sites ($F_{(1,48)} = 6.005$, $p < 0.05$), with 0.617 and 0.536 SQI values, respectively. Our results suggest that all the individual restored sites suffer from a reduction in their overall SQI values and reveal a trend in accordance with the time passed since restoration, where the oldest restored site of Gov scored highest (0.652 and 0.574 for natural and restored, respectively; $F_{(1,16)} = 2.642$, $p < 0.05$), followed by Hagor (0.615 and 0.552; $F_{(1,16)} = 0.712$, $p = 0.057$), and the most recently restored site, Afik, was ranked 0.608 and 0.507 scores ($F_{(1,16)} = 10.364$, $p < 0.05$). The biological attributes presented significant differences between the natural and the restored areas, as found for the Gov, Afik, and all sites together ($F_{(1,48)} = 8.189$, $p < 0.05$). The physical properties presented significant differences between the natural and the restored

Table 3
Varimax rotation PCA results of all sites for scoring soil properties from the restored and the natural sites combined. The bolded soil properties refer to the absolute highest loading within 10% of the factor loading. The overall model had a cumulative percentage of 68.1%. AWC: available water content, SOM: soil organic matter, EC: electrical conductivity, K: potassium, and P: phosphorus. Bold numbers refer to the highest factor loading for each soil indicator by its corresponding PC.

	PC1	PC2	PC3	PC4	PC5
Eigenvalues	2.579	1.541	1.348	1.029	0.993
Proportion of variance	15.089	14.289	13.863	13.271	11.596
Cumulative percentage	15.089	29.378	43.241	56.512	68.108
No. of properties	2	4	2	2	1
AWC Score	0.128	−0.065	**−0.672**	0.395	−0.313
Infiltration Score	−0.226	**−0.606**	0.005	0.393	0.420
pH Score	0.129	**0.490**	−0.392	0.135	0.364
EC Score	**0.662**	0.100	−0.429	0.034	−0.041
$N\text{-}NH_4^+$ Score	−0.058	−0.116	**0.813**	0.222	0.078
$N\text{-}NO_3^-$ Score	0.325	**0.608**	−0.148	0.230	−0.101
P Score	0.055	0.029	0.214	−0.023	**0.827**
K Score	−0.199	**0.747**	0.037	−0.002	0.116
SOM Score	0.025	0.069	0.008	**0.847**	0.074
Protein Score	**0.859**	−0.007	0.010	0.037	0.099
Polysaccharide Score	0.497	0.060	0.068	**0.556**	−0.372

areas in Afik and all sites together ($F_{(1,48)} = 4.031$, $p < 0.05$). In the chemical properties of the Hagor site, the soil indicators have significant differences between the natural and restored sites ($F_{(1,16)} = 4.039$, $p < 0.05$).

4. Discussion

Mining restoration depends on the practices used and the time since the restoration was applied (Andrés and Mateos, 2006). Evaluating restoration success using the SQI approach could be used as a management tool, mainly in an arid environment where the vegetation is sparse, and most soil recovery processes are long-term (Costantini et al., 2016; Mukhopadhyay et al., 2014). Most studies on ecological mining restoration have focused on forest, grassland, and wetland ecosystems, while fewer have examined arid regions (Guan et al., 2019). Extensive literature exists on indicator selection for evaluating the ecological restoration success and recovery rate after mining (Martins et al., 2020). Several physical, biological, and chemical soil properties were suggested for developing the SQI to assess the effect of topsoil restoration practices (topsoil compared to the natural area) in phosphate mines in a hyper-arid region. The properties were selected and analyzed to determine the restoration efforts and identify spatial and temporal variations in the successional processes (Costantini et al., 2016). Significant differences in the SQI were found between several soil properties' scores and between SQI models in the different sites, indicating a general trend of higher SQI in the natural sites than in the restored ones. It was found that the biological indicators were the most affected properties with significant differences in Gov, Afik, and all sites together, followed by the physical ones with significant differences in Afik and all sites, and the chemical components showing significant differences only in Hagor site. Therefore, it is suggested that the selection of soil properties should focus more on soil biological and physical properties, which could help

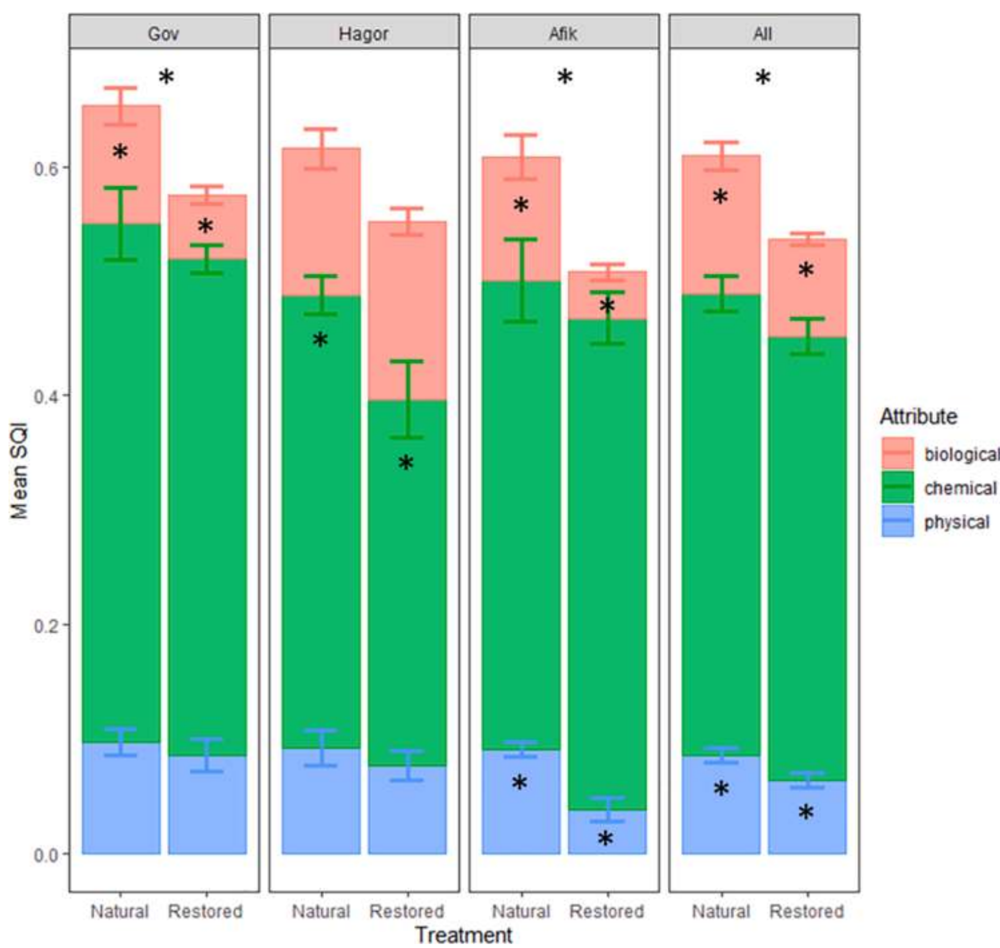


Fig. 6. Stack graph of indicator groups for the restoration practice for each site and their combination. An asterisk under the site name represents an overall significant difference between the restoration practices. The asterisks within the colored bars show significant differences between the groups of indicators (i.e., biological, chemical, and physical).

evaluate phosphate mines' restoration in an arid region.

4.1. Indicator selection: A minimum dataset for soil quality measurement

SQIs are useful tools to assess restoration efforts and evaluate the recovery rates (Muñoz-Rojas et al., 2016). Although some indicators could be more relevant than others for capturing soil differences (Bastida et al., 2008; Muñoz-Rojas et al., 2016), using one soil property constitutes a critical limitation (Muñoz-Rojas et al., 2016). Consequently, the SQI is increasingly used to estimate restoration success, determine the direction of change with time, and highlight the differences between restoration practices (Shukla et al., 2006). However, creating a minimum dataset by selecting indicators that can sufficiently and accurately assess mining restoration efforts is a complicated matter (Bünemann et al., 2018; Muñoz-Rojas et al., 2016). Our results demonstrate the need for further refinement after initially selecting a minimum dataset to reduce additional complexity and adequately represent the soil quality conditions for arid regions. The soil properties with significant differences between mining areas and natural areas were infiltration rate, SOM, and polysaccharides. Previous studies have shown that SOM is a reliable soil indicator, pointing to mining restoration success and land degradation (Bodlák et al., 2012; Chaudhuri et al., 2015). SOM was one of the soil properties that showed a clear scoring reduction trend in the topsoil mining sites compared to the natural areas. Moreover, the infiltration rate showed a similar pattern in all sites with a higher infiltration rate in the restored sites, resulting in lower scores than natural sites. N-NH_4^+, P, and K were selected as potential nutrient availability indicators since they are key nutrients, although only a small fraction may be available to plants (Andrés and Mateos, 2006). These are essential for plant regeneration, which is necessary for successful restoration processes in arid regions. Eventually, only P was found significant in the integrated model, whereas N-NH_4^+ was significantly different in the Afik site only, and K had no notable differences in any of the sites.

Polysaccharides and proteins indicate biocrust development, which plays a considerable role in stabilizing the soil surface, affecting the infiltration rate that reduces erosion by water and wind in arid regions (Zaady et al., 2016). The development of biocrusts, composed of cyanobacteria, moss, and/or lichens, could be used as an indicator for mining soil recovery and restoration success (Dangi et al., 2012; Mukhopadhyay et al., 2017; Muñoz-Rojas et al., 2016). Restoration of mining areas accelerates the development of biocrust structures and functions to assess and speed up the recovery of a degraded ecosystem (Zaady et al., 2016). Soil micro-organisms' diversity and abundance provide surrogates for soil recovery. Polysaccharides are related to soil microbial biomass that is extensively used in SQI assessments (Mager and Thomas, 2011). Usually, increases in polysaccharides are considered beneficial to soil development in arid regions (Mendoza-Aguilar et al., 2014). However, additional analyses, such as phospholipid fatty acid (PLFA), could be used to assess the difference in the microbial community over time and describe its structure and composition (Bandyopadhyay and Maiti, 2019; Ben-David et al., 2011; Dungait et al., 2011). Cyanobacteria are some of the most dominant life forms found in biocrusts in arid environments, including the Negev Desert (Chamizo et al., 2019; Ferrenberg et al., 2015; Karnieli et al., 1999; Zaady et al., 2010). Although biocrust only occupies the upper few millimeters of the soil profile (Dixon, 2009), cyanobacteria greatly influence different soil properties and the overall SQI in various ways. Cyanobacteria stabilize the soil surface, control runoff, infiltration, and percolation, increase the soil moisture content, and improve the nutrient content and soil fertility (Belnap, 2006; Chamizo et al., 2019; Kuske et al., 2012), which are all highly related to soil recovery after mining. Studies have shown that biocrust development affects hydrological processes in drylands, resulting in a decline in infiltration rate and soil moisture (Eldridge et al., 2020). These soil features are affected by the biocrust community composition and the soil properties (e.g., soil texture). Among the microbial communities, cyanobacteria are the most resilient (Belnap and Eldridge, 2001) and can survive on minimal and irregular amounts of water (Mazor et al., 1996), typical conditions in arid regions. Eventually, polysaccharides were significantly lower in the Afik site and in the combined model than restored and natural plots. These could be related to the time passed since restoration, where the Afik site is the youngest restored site—referring that the time passed since restoration wasn't enough for the biocrust to recover.

4.2. Evaluation of restoration practice with time since restoration

Soil quality estimations in restored mining areas either compare pre- and post-recovery conditions or disturbed land and nearby undisturbed land to assess the restoration process's rate and quality (Sheoran et al., 2010). By comparing the restoration practices between both the natural and restored sites, significant differences were seen across indicator groups (mainly biological and physical indicators) and overall SQI. Only a few significant differences between the natural and restored sites, as a result of topsoil restoration, were previously documented (Muñoz-Rojas et al., 2016). When observing each study site separately, significant differences between the natural and restored sites were found. The topsoil restoration practices mitigate the destructive severity of mining (Albert, 2015), thus, reducing the differences between the restored and natural plots, seen mainly at the Gov plot. In drylands, topsoil restoration is a critical practice due to the unpredictable climatic conditions with the potential for long and frequent droughts, along with the severely limited abundance of seeds, nutrients, and micro-organisms that are considered to be key elements in soil restoration, limit plant development, and growth in arid regions (Golos et al., 2016; Muñoz-Rojas et al., 2016).

We found that topsoil restoration enabled partial recovery of the Hagor and Gov sites. The period between the ecological restorations may have promoted natural restoration processes, as shown in the Gov site. However, the slightly higher levels of AWC, proteins, and polysaccharides in the restored plots shown at the Hagor site can be attributed to higher site suitability. Thus, low polysaccharide concentrations indicate a delay in biocrust development over the past 20 years. The initial process of soil recovery begins by establishing physical, followed by biological indicators, and therefore, the topsoil amendment method is crucial for promoting soil restoration efforts. Further study could test the differences in restoration practices with and without topsoil and their implications for soil quality and restoration success. Thus, integrating physical, chemical, and, more importantly, biological indicators is necessary to evaluate soil recovery in arid environments.

4.3. Assessment of soil quality index

The SQI combines various soil properties to provide a single value representing the overall soil health . The current SQI approach was based on the varimax rotation PCA scores and was found to be valid for assessing mine restoration in arid regions (Asensio et al., 2013; Mukhopadhyay et al., 2014; Pietrzykowski, 2014). Defining restoration practices in mining areas required identifying specific soil indicators associated with soil quality (Menta et al., 2014). Our results show significant differences in most study sites, mainly due to biological and physical soil indicators, such as SOM, infiltration rate, and polysaccharides, with a significant difference in these indicators between the natural and restored plots, as shown in the SQI (Fig. 6). In contrast, the group of chemical indicators showed no significant differences between most sites for the overall soil quality (except for Hagor). The soil indicators used for this task may differ depending on local conditions and the disturbance's extent. Therefore, we concluded that restoring the physical and biological soil indicators is a complex process in mine restoration. These required rehabilitating the biological indicators of the biocrust community, which are especially crucial in hyper-arid areas. Biocrust has a multifunctional effect on soil function and structure. They regulate soil nutritional stocks through N fixation (Elbert et al., 2012), influencing hydrological processes (Chamizo et al., 2016), and stabilizing soil, among other aspects. In general, our results reflect a slow recovery of the SQI in the restored sites, demonstrating that achieving the quality of the natural areas requires a long-term recovery process. Moreover, the physio-biological indicators were found to be more suitable for reliably assessing mining restoration practices.

5. Conclusions

This study took place in an open-pit phosphate mining area, which is located in a hyper-arid environment. Developing an SQI and incorporating physical, biological, and chemical properties of soil restoration practice was accomplished. In conclusion, using the SQI method on the different restored sites shows reduced soil quality compared to the natural sites. The biological and physical indicators demonstrate the importance of the topsoil restoration method for recovering the biocrust community. For the overall SQI, chemical indicators alone cannot significantly distinguish between restoration practices, either because of natural processes or the change in soil chemical characteristics during mining practices in such an arid environment. Given these results, further SQI assessments and restoration follow-ups should focus on the vitality and evolution of the soil microbial community and biocrust development after using the topsoil method in restored phosphate mines. Moreover, the groups of biological and physical indicators should be considered as the primary tools in any SQI assessment to estimate the recovery success of mining sites in arid areas, where vegetation is scarce and soil recovery is a long-term process.

CRediT authorship contribution statement

Nathan Levi: Methodology, Software, Validation, Writing - review & editing. **Noa Hillel:** Formal analysis, Investigation, Methodology, Software, Validation, Writing - original draft, Writing - review & editing. **Eli Zaady:** Methodology, Writing - review & editing. **Guy Rotem:** Project administration. **Yaron Ziv:** Project administration, Writing - review & editing. **Arnon Karnieli:** Project administration, Writing - review & editing. **Tarin Paz-Kagan:** Formal analysis, Investigation, Methodology, Software, Validation, Writing - original draft, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2021.107571.

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