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Single Session of Chiseling Tillage for Soil and Vegetation Restoration in Severely Degraded Shrublands

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Abstract: While tillage of agricultural lands has been used extensively, its utilization for restoring degraded semi-natural lands is rare. This study was conducted in the arid southern Israel in a shrubland which has faced severe degradation processes over time, including soil erosion and compaction, and negation of vegetation recovery. In 2014, research plots were established for assessing the impact of a single chiseling session on the ecosystem's restoration capacity. The study treatments included deep chiseling (35 cm), shallow chiseling (20 cm), and control (no-tillage). Data on spontaneously-established vegetation was collected one, two, and three years after the plots' establishment, and soil data was collected once—three years after the plots' establishment. Assessments of the vegetation parameters revealed a general similarity between the two chiseling treatments, which were generally better than those of the no-till plots. The soil properties revealed generally greater soil quality under the two chiseling treatments than that under the control plots, and a somewhat better soil quality for the deep chiseling than that for the shallow chiseling. Overall, results of this study show that in severely degraded lands, self-restoration processes are hindered, negating the effectiveness of passive restoration practices, and necessitating active intervention practices to stimulate restoration processes.

Keywords: available water capacity; central Negev; microbial biomass and activity; microtopography and geodiversity; plant cover; soil aeration; soil moisture content; soil roughness; organic carbon; species richness and diversity

1. Introduction

Among other factors, soil compaction in open, semi-natural lands is widely acknowledged as imposed by anthropogenic activities. Specifically, anthropogenic traffic, by either pedestrians, bicycles and motorcycles, or off-road vehicles [1], increases the soil compaction, resulting in adverse impact on the soil structure, aggregation, aeration, hydraulic conductivity [2], and microbial biomass and activity [3]. Such soils are mostly compactable under wet to moist conditions, where friction among its particles decreases, allowing them to slide over each other and easing the deformation of the soil structure [4].

Semi-natural lands that have become degraded often undergo passive restoration measures, aimed at halting disturbances and restoring some of the natural functions and ecosystem services. Among these measures, the fencing of the target lands for negating the access of livestock or human is most common. Despite necessitating a relatively long timeframe for recovery [5], such passive strategies could effectively restore degraded lands, allowing self-restoration processes to take place, resulting in the improvement of soil conditions and increase in net primary productivity over time.

At the same time, and despite necessitating relatively shorter time for recovery, active restoration strategies of semi-natural or abandoned lands are less common. This is partially attributed to the comparatively higher costs involved in such intervention procedures [6]. An example is the planting of mixed trees in degraded lands, which was reported to effectively recover the functioning of ecosystem services [5,6]. Another example for an active restoration scheme was reported for Poland, where inversion tillage of a degraded land was conducted for mitigating anthropogenic disturbances, aimed at allowing the establishment of semi-natural grasslands [7]. At the same time, the use of tillage for restoring severely-degraded shrublands is not so common. Yet, such a strategy might be necessary in events where the target lands have been prone to extreme degradation. Specifically, such a management practice might be particularly relevant for drylands, where the limited access to water negates the re-establishment of vegetation and hinders self-restoration processes.

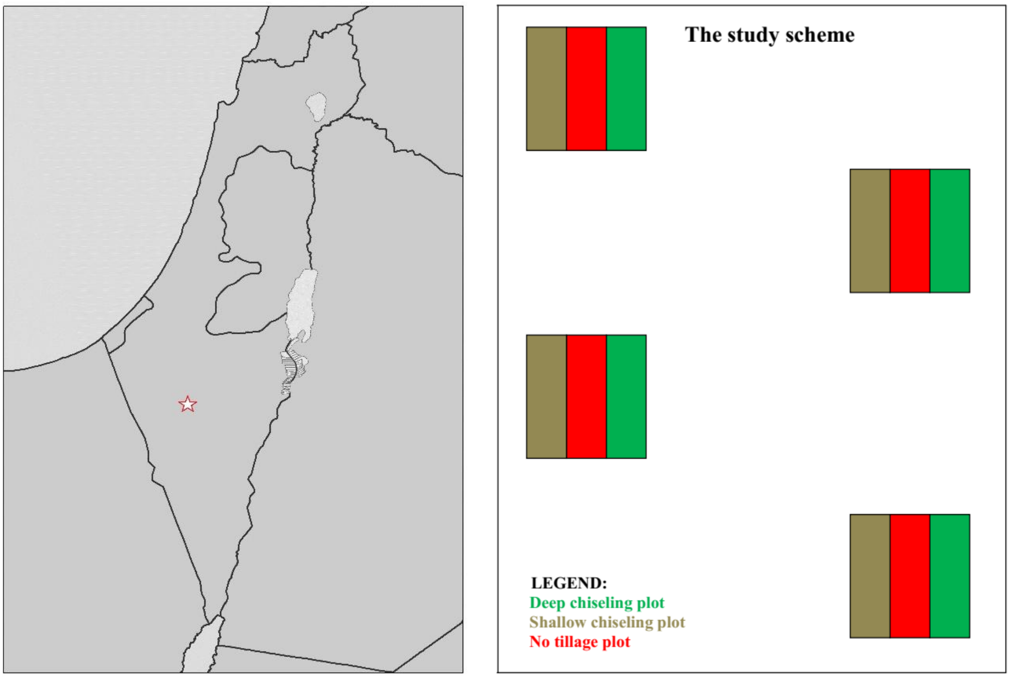
Compared to conventional plow tillage, chiseling plow has two main advantages: (i) loosening of compacted layers while not smashing and crumbling the soil; and (ii) negating the inversion of soil horizons, thereby minimizing disturbance of pedogenesis. The moderate impact of chiseling on pedogenic processes has been realized by several studies. For example, in croplands in south-western Brazil, chiseling was reported to decrease soil compaction in the 10–20 cm depth layer compared to that under no-till [8]. Also, a recent study in croplands in the US state of North Dakota, showed that compared to no-till, chiseling decreased the soil organic carbon pool in the 0–15 cm depth only, while not affecting it in the deeper depths [9]. Regardless, similar to other tillage means, heavy compaction of soil is expected in chiseled croplands with recurring traffic by agricultural machinery, negating the agro-technical advantages of this—comparatively reduced-intensity tillage method.

This study was conducted at the extremely degraded plateau of Sde Zin, which is located in the arid central Negev of Israel. In the early 1970s, the site was proclaimed a national park. Yet, ongoing, intensive traffic by pedestrian and off-road vehicles until 2007 led to severe degradation processes, defined by the extreme compaction of its soil, erosional processes, and negation of vegetation growth. Therefore, in 2014, research plots were established, aimed at assessing the impact of a single chiseling session—to either shallow or deep depths—on the restoration capacity of this degraded shrubland. Parameters of spontaneously-established vegetation were studied after one, two, and three years following the establishment of the plots, and the soil properties were studied three years after the establishment of the plots. The study's main hypothesis was that the single chiseling session alleviates the soil compaction, improving its hydraulic features and easing re-establishment of vegetation. The secondary hypothesis was that due to the severe compaction and degradation of the soil, shallow chiseling has been capable only of moderately restoring the geo-ecosystem, while deep chiseling resulted in a more pronounced restoration.

2. Materials and Methods

2.1. Regional Settings

The study was conducted in Sde Zin (30° 86′ N, 34° 79′ E, 475 m above sea level: Figure 1a), which covers a plateau of ~10 km^2, sprawling between the Zin Valley to the east and Halukim Ridge to the west. Climate of the region is arid, with cold winters and mildish-hot summers. Mean daily temperature ranges between 9 °C in January and 24 °C in July. Mean daily relative air humidity ranges between 68% and 54%, respectively [10]. Mean annual cumulative precipitation is 93 mm, with a high inter-annual variability [11]. Lithology is comprised of the Dead Sea Group's conglomerate and loess of the Pleistocene [12], and the soil is classified as Calcic Xerosol [13].



(**a**) (**b**)

Figure 1. Map of Israel, with an indication of the study site (**a**); Schematic illustration of the study design (**b**).

Due to its being a tourist attraction, over decades the site has been prone to heavy traffic by pedestrians, bicycles, motorcycles, and off-road vehicles, leading to considerable degradation processes, including extreme soil compaction, severe erosional processes, and negation of vegetation recovery. In 1971—alongside with extensive lands across the region—a part of the Sde Zin was proclaimed as the Gan Ha'Psalim National Park. Yet, the heavy traffic has proceeded, negating processes of self-restoration of the ecosystem. In 2007, the site was legally registered as a national park, allowing for better control of traffic. Means to control this traffic have included guidance, inspection, on-site signposting, and non-consecutive placement of boulders along the main dirt-roads which transect the site.

Data on precipitation throughout the study years (2015–2017) were obtained from the Sde Boqer meteorological station, which is located at a distance of approximately 1 km from the study site. The recorded annual cumulative precipitation was 125 mm, 87 mm, and 53 mm in the rainy seasons of 2014/15, 2015/16, and 2016/17, respectively.

2.2. The Study Design, Soil Sampling, and Analysis

The research plots were established in spring 2014 (under dry soil conditions), at a site that has been included in the national park. The study design encompassed four blocks, each containing three plots, of which one plot pertains to each of the following treatments: (1) one session of deep chiseling to a depth of 35 cm; (2) one session of shallow chiseling to a depth of 20 cm; and (3) control (Figure 1b and Appendix A). The aerial cover of each plot was 180 m^2 (30 m length $\times$ 6 m width). The minimal distance between each two adjunct blocks was 50 m [14,15].

Assessment of spontaneously-established vegetation was conducted one, two, and three years after the establishment of the plots, i.e., at the peak of the 2015, 2016, and 2017 growing seasons (spring). The vegetation data was collected from three 1 $\times$ 1 m randomly selected sub-plots per plot.

The collected data included cover percentage of annual and perennial species (for 2015 and 2017 only), and number of annual and perennial species (for each of the years of 2015, 2016, and 2017). Also, the data was utilized for calculating the species richness, Shannon's diversity index, and Fisher's alpha parameter.

On-site measurements and sampling of soil were conducted in spring 2017, three years after the establishment of the plots. In each plot, measurements of ground surface roughness were conducted by the chain method in three randomly selected spots. This measurement is based on the principle that when a chain of given length (L1) is placed on a surface, the horizontal distance between the chain edges (L2) will decrease as the roughness increases [16]. The surface roughness (in %) was calculated according to the equation: $1 - (L2/L1)$. Then, measurements of the soil penetration resistance (using a dynamic penetrometer: [17]) and sampling of soil were conducted at the same three spots and at two depths, of 0–5 cm and 20–25 cm. Soil sampling included an undisturbed 100-mL (5 cm height × 5 cm diameter) core, and a 300-mL bag of disturbed soil, both of which were obtained from each spot and depth.

The soil core samples were studied for bulk density (the core method: [18]), and field capacity (by using a sand-kaolin box: Eijkelkamp©, Giesbeek, The Netherlands). The disturbed soil samples were studied for permanent wilting point (by using a pressure-membrane apparatus: Eijkelkamp©, The Netherlands). Subtracting the values obtained for permanent wilting point from those obtained for field capacity enabled the calculation of available water capacity. The disturbed soil samples were also studied for texture (by the hydrometer method: [19]), gravimetric moisture content (by oven-drying at 105 °C for 24 hr: [20]), calcium carbonate content (by using a calcimeter: [21]), and total organic matter content (by the dry combustion method [22], after fumigation with diluted hydrochloric acid [23]. The results were then divided by 1.724 to calculate the total organic carbon concentration).

For bacterial relative abundance, an additional set of soil samples was collected in sterile 50 mL tubes, kept on ice upon collection, and stored in −80°C for eight hours for DNA extraction. Before DNA extraction, soil was cleaned from the plant root, floral and faunal materials, and stones, and then homogenized. Later, 0.6 g of soil was subjected to DNA extraction by using DNeasy PowerSoil HTP 96 Kit (Qiagen©, Hilden, Germany). Upon extraction, the 16S ribosomeal DNA (rDNA) resembling of bacterial abundance was performed in triplicates on the 7500 Real time PCR (Applied Biosystems© Foster City, CA, USA), by using SYBR Green quantitative polymerase chain reaction (qPCR) as following: 5 µL of DNA template, 10 µL of PerfeCta SYBR Green FastMix, Low ROX (Quanta BioSciences© Beverly, MA, USA), 2 µL of 250 nM of forward F341 (5′-CCT ACG GGA GGC AGC AG-3′) and reverse R519 (5′-GWA TTA CCG CKG CTG-3′) primers [24], and 3 µL PCR-free molecular grade water (Sigma©, Rehovot, Israel) as per the manufacture protocol (Quanta BioSciences©). The soil samples' 16S rDNA standard was used to quantify the number of fragments [24].

Yearly number of vegetation sub-plots (n) was 4 blocks × 3 treatment plots × 3 sub-plots = 36. Number of soil samples (n) was 4 blocks × 3 treatment plots × 3 spots × 2 depths = 72.

2.3. Statistical Analysis

To evaluate the effect of treatment on the various soil characteristics, we used Linear Mixed Effects models. The fixed effects were treatment type, depth, and their interaction. An exceptional to that was the surface roughness, which was measured only at the ground surface, and therefore the model for its analysis included only the fixed effect of treatment. The random effect was block identity. Models were fitted using function 'lme' from package 'nlme' [25] in R [26].

3. Results and Discussion

3.1. Above-Ground Processes

Visually, in the studied plots, two main signs indicated the effect of the treatment. The first was the roughness of the ground surface, which was clearly greater under the two chiseling treatments than that under the control plots. This is consistent with the results obtained for the chain method, revealing significant and approximately tenfold greater mean roughness of the ground surface under each of the chiseling treatments than that under the control plots (Table 1). This accords with the general conception of the ground surface roughness being positively affected by tillage. Also, tillage-induced roughness has been acknowledged as having the capacity to control surface processes, with the increased on-site retention of water and hindering of overland flow [27]. Mean ground surface roughness in the deep chiseling plots was significantly and over 30% greater than that in the shallow chiseling plots (Table 1). In addition to the impact on surface processes, these microtopographic-induced changes are expected, over time, to boost patch-scale geodiversity [28], with the resultant increased heterogeneity in microhabitat conditions [29], and greater vegetation species diversity [30].

Table 1. Treatment effect on the soil surface roughness (%), penetration resistance (MPa), bulk density (ρ_b: Mg m^{-3}), total porosity (S_t, %), gravimetric moisture content (Θ_g: %), available water capacity (AWC: mm water per 5-cm soil layer), total organic carbon concentration (SOC: g kg^{-1}), bacterial relative abundance (16S rDNA fragment number g^{-1}), SOC stratification ratio (g kg^{-1} in the 0–5 cm depth/g kg^{-1} in the 15–20 cm depth), and calcium carbonate content ($CaCO_3$: %).

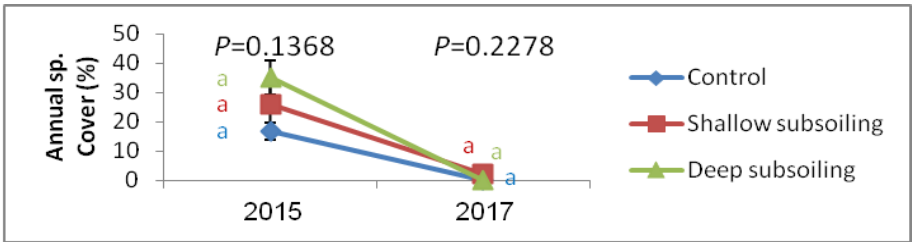
	P Value	Deep Chiseling	Shallow Chiseling	Control
Surface roughness	**<0.0001**	6.1 a (0.5)	4.6 b (0.5)	0.5 c (0.3)
Penetration resistance	**0.0007**	0.38 b (0.06)	0.39 b (0.07)	1.62 a (0.19)
ρ_b	**0.0009**	1.31 b (0.02)	1.36 b (0.02)	1.55 a (0.03)
S_t	**0.0009**	50.6 a (0.6)	48.8 a (0.9)	41.1 b (0.9)
Θ_g	**0.6593**	5.8 a (0.6)	5.3 a (0.5)	3.3 a (0.2)
AWC	**0.5095**	7.2 a (0.5)	6.7 a (0.4)	5.3 b (0.3)
SOC	**0.0498**	22.6 ab (1.4)	19.7 b (1.2)	24.2 a (1.5)
Bacterial relative abundance	**<0.0001**	6.03×10^7 a (1.24×10^7)	3.6×10^7 b (7.03×10^6)	1.73×10^7 c (3.08×10^6)
SOC stratification ratio	0.3871	1.01 a (0.08)	0.82 a (0.04)	0.93 a (0.09)
$CaCO_3$	0.2322	27.5 a (0.4)	26.8 a (0.5)	26.3 a (0.5)

Notes: Bold *P* value indicates a significant effect. Means within a row followed by a different letter differ at the 0.05 probability level according to Tukey's honestly significant difference (HSD). Numbers within parentheses are standard error (SE) of the means.

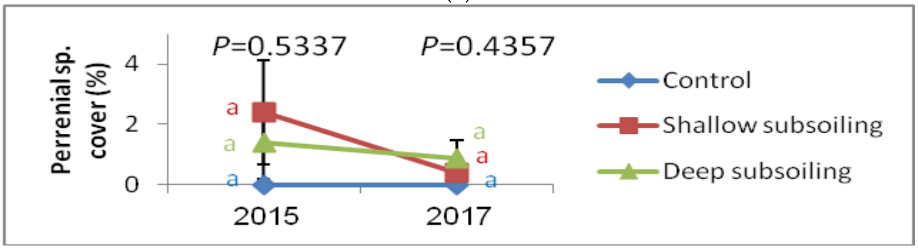
Visual indications for surface processes of water runoff and soil erosion were observed across the study site, beyond the research plots. These included extensive areas with smooth surfaces, indicating sheet-flow erosion, as well as the sporadic occurrence of rills, which indicate concentrated erosion. Surface processes are known to cause size-sorting of soil particles, with the generally easier and faster redistribution (sorting out) of the smaller-sized fractions [31]. However, the soil texture was not affected by treatment, with similar contents of sand (33.1 ± 1.1%), silt (49.6 ± 3.3%), and clay (17.3 ± 2.8%) among the three study treatments. This could be attributed to the relatively short time-span between the establishment of plots and sampling. Nor was the texture affected by the soil depth, having a loamy texture throughout the profile.

The second visual sign was the spontaneously-established vegetation cover, which existed under the two chiseling treatments to a much greater extent than that under the control plots. It is suggested that in addition to hindering water overland flow, and thereby increasing its on-site infiltration, the chiseling-induced ground surface roughness also eases the trapping of plant seeds, which become ready for on-site germination. To some extent, this accords with previous studies which highlighted the positive impact of surface roughness on trapping of seeds transported by water [32] or wind [33].

The visual indications of vegetation cover were consistent with the data analysis, which revealed somewhat (but not significantly) greater mean cover percentage of annuals (Figure 2a) and perennials (Figure 2b) under the two chiseling treatments than that under the control plots. For the annual species, this was more noticeable for 2015, where the mean cover was ~50% to twofold greater under the chiseling treatments than that under the control plots. For the perennial species,



(**a**)



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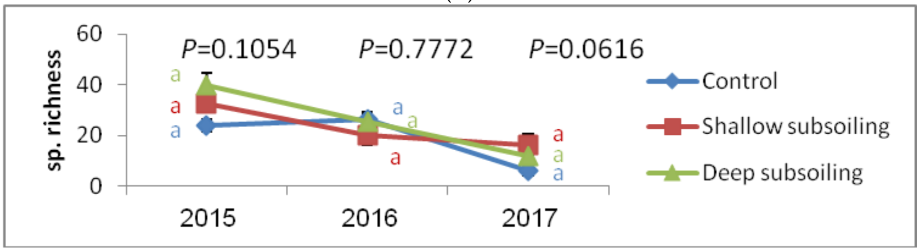
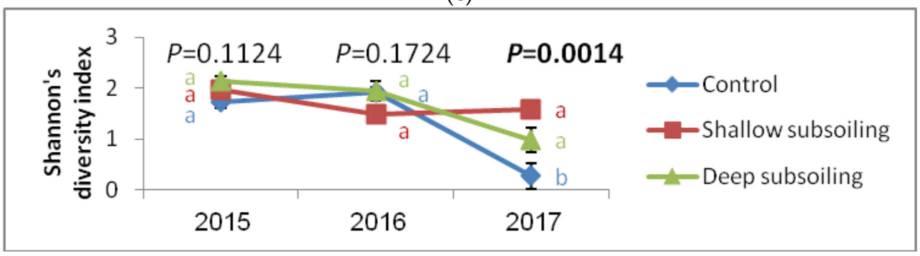
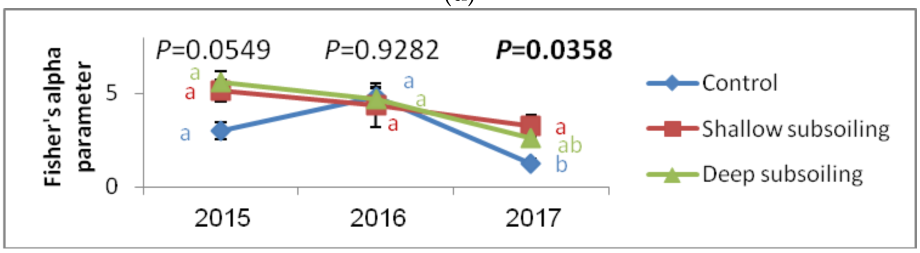


(**c**)



(**d**)



(**e**)

Figure 2. Treatment effect (according to year) on vegetation parameters, including: annual species cover (**a**); perennial species cover (**b**); species richness (**c**); Shannon's diversity Index (**d**); and Fisher's alpha parameter (**e**). Notes: Bold *P* value indicates a significant effect. Means within a year followed by a different letter differ at the 0.05 probability level according to Tukey's honestly significant difference (HSD). Error bars represent standard error (SE) of the means.

This was noticeable for both of the years of 2015 and 2017, with the zero cover under the control plots. Overall, the differences for the vegetation cover percentage among the three treatments in 2017 were rather small. This is attributed to the extremely dry rainy season in 2016/17, with the cumulative rainfall of only 57% of the inter-annual average. Regardless, the differences for these variables between the two chiseling treatments were inconsistent.

Similar to the trend for vegetation cover, the shallow and deep chiseling treatments faced a decreasing trend throughout the three-year study period for each of the means of species richness (Figure 2c), Shannon's diversity index (Figure 2d, despite a minor exception for the shallow chiseling treatment in 2017), and Fisher's alpha parameter (Figure 2e). At the same time, the control plots faced—for each of these variables—a slight increase between 2015 and 2016, and then a sharp decrease between 2016 and 2017. However, mostly, the treatment effect on means of these variables was not significant. The only exceptions were recorded for the Shannon's diversity index in 2017, where means under the two chiseling treatments were significantly greater than those under the control plots; and for the Fisher's alpha parameter, where mean under the shallow chiseling treatment was significantly greater than that under the control plots (and the deep chiseling treatment taking place between them). For each of the last three parameters, means under the deep chiseling treatment were slightly greater than those under the shallow chiseling treatment in 2015 and 2016, while an opposite state was recorded for 2017. This suggests a slight advantage for the deep chiseling treatment under a high-to-normal precipitation regime, and a slight advantage for the shallow chiseling treatment under an extremely low precipitation regime. However, a much longer period of study is needed to verify this observation.

Data on the recorded vegetation species, according to year and treatment are detailed in Appendix B.

3.2. Below-Ground Processes

The main goals of tillage are breaking the mechanical crust cover, loosening soil compaction, increasing soil aeration, and reducing the ground surface penetration resistance [8,34,35]. However, many studies have revealed that compared to no-till systems, conventional tillage causes undesired, opposite impacts, resulting in the deformation of soil structure [36], and increasing bulk density and penetration resistance [37]. Yet, compared to regular agricultural lands, where the largest part of soil compaction is attributed to recurring agricultural machinery traffic [38,39], the relatively slight soil compaction in the tillage plots in our study could be attributed to the scant-to-absence of any type of traffic after the single chiseling session. This is exemplified by the significant and three-quarters smaller mean penetration resistance and 12–15% smaller mean bulk density of soils under the chiseling treatments than that under the control plots (Table 1).

Therefore, assuming homogenous particle density (ρ_p of 2.65 Mg m^{-3}: [40]), the calculated, significantly greater total porosity under the deep and shallow chiseling treatments than that under the control plots is expected to allow much better aeration of soil. Bulk density and total porosity were not significantly different between the two chiseling treatments, and their means were 4% smaller and 3% greater, respectively, under the deep chiseling plots than those under the shallow chiseling plots (Table 1). The strongly negative and significant ($r = -0.57$; $P < 0.0001$) correlation between the ground surface roughness and bulk density, further emphasizes the treatment-induced physical quality of soil, which follows the order of deep chiseling > shallow chiseling > no-tillage.

Also, the smaller the compaction of soil is, the better its hydraulic properties [41]. In our study, this was indicated by the 65–70% greater mean gravimetric soil moisture content under the two chiseling treatments than that under the control plots (Table 1). However, this effect was not significant. Despite not being available for vegetation uptake, the determined hygroscopic-level moisture of soil still indicates its physical quality [42], revealing better soil conditions under the two chiseling treatments than those under the control plots. This was further verified by the strongly positive and significant ($r = 0.69$; $P < 0.0001$) correlation between gravimetric moisture content and available water capacity. Further, though not being significantly affected by treatment, the mean available water capacity under the two chiseling treatments was 26–35% greater than that under the control plots. Also, despite that these variables were not significantly different between the two chiseling treatments, the means of gravimetric moisture content and available water capacity were 9% and 7% greater, respectively, under the deep chiseling plots than those under the shallow chiseling plots (Table 1).

In spite of these positive impacts of the single chiseling session on the soil physical quality, it significantly and negatively affected the soil organic carbon concentration. Mean of this variable was 7% and 22% greater under the control plots than that under the deep and shallow chiseling treatments, respectively (Table 1). This negative effect on soil organic carbon is attributed to the increased aeration provided by tillage action, with the expected stimulation of microbial activity, and the resultant greater rates of soil organic carbon decomposition [43]. These effects are consistent with the mean bacterial relative abundance, which was significantly and 3.5 and 2.1 times greater under the deep and shallow chiseling treatments, respectively, than that under the control plots (Table 1).

Actually, the bacterial relative abundance was the only soil feature which was significantly different between the two chiseling treatments. Mean of this variable was 69% greater under the deep than that under the shallow chiseling treatment (Table 1), highlighting the better biological quality of soil under the former than that under the latter. Also, this effect suggests that compared to the remainder of the soil properties, the microbial activity is the most sensitive to tillage. This consists with previous studies, which highlighted the comparatively high sensitivity of microbial biomass and activity to tillage practices [44–46]. Also, the strongly positive and significant (r = 0.76; $P < 0.0001$) correlation between ground surface roughness and bacterial relative abundance, emphasizes the high sensitivity of the latter to the tillage-induced, above-ground changes.

Despite not being significantly affected by treatment, the soil organic carbon stratification ratio, was balanced (~1) for the deep chiseling treatment, and negative (<1) for the shallow chiseling treatment. Regardless, the negative soil organic carbon stratification ratio in the control plots (Table 1) highlights their severe state of soil degradation, with the absence of a characterizing the A horizon at the ground surface (see: [47]).

The soil calcium carbonate content was relatively high across the study site, and not significantly affected by treatment (Table 1). It seems that this is related to the short time span between the establishment of plots and sampling. It is expected that over a longer time span, the better hydraulic properties of soil under the tillage treatments will increase the leaching of calcium carbonate from the tilled layer. One way or another, the restriction of soil microbial activity [48] and reduction of plant-available macronutrients [49] by high contents of calcium carbonate, seem to retard restoration processes under the three studied treatments. To some extent, this could explain the relatively sparse vegetation cover (even) in the chiseling plots.

Unexpectedly, the effect of soil depth was small and non-significant for a large part of the studied variables. This could be attributed to the severe disturbance of ground surface, caused by the combined effect of the extreme compaction and erosional processes, negating 'normal' pedogenic processes of horizonation. An exception to that is the mean penetration resistance, which was significantly and 25% greater in the deeper depth than that in the shallower depth. At the same time, the mean gravimetric moisture content, though not being significantly affected by depth, was twofold greater at the deeper depth, than that at the shallower depth. This effect is attributed to the greater evaporation rates at the ground surface than those at the subsoil layers [50]. Regardless, the bacterial relative abundance was significantly and approximately one order of magnitude greater in the shallower depth than that in the deeper depth, indicating the considerably better biological quality at the former (Table 2).

Table 2. Depth effect on the soil penetration resistance (MPa), bulk density (ρ_b: g cm^{-3}), total porosity (S_t, %), gravimetric moisture content (Θ_g: %), available water capacity (AWC: mm water per 5-cm soil layer), total organic carbon concentration (TOC: g kg^{-1}), bacterial relative abundance (16S rDNA fragment number g^{-1}), and calcium carbonate content ($CaCO_3$: %).

	P Value	0–5 cm	15–20 cm
Penetration resistance	**0.002**	0.71 b (0.12)	0.89 a (0.16)
ρ_b	0.2697	1.39 a (0.02)	1.41 a (0.03)
S_t	0.2697	47.3 a (0.9)	46.6 a (1.1)
Θ_g	0.1587	3.1 a (0.1)	6.5 a (0.5)
AWC	0.3407	5.7 a (0.2)	7.0 a (0.5)
SOC	0.3603	21.1 a (1.2)	23.3 a (1.0)
Bacterial relative abundance	**0.0047**	6.58×10^7 a (7.43×10^6)	9.75×10^6 b (8.64×10^5)
$CaCO_3$	0.5121	27.1 a (0.4)	26.6 a (0.3)

Notes: Bold *P* value indicates a significant effect. Means within a row followed by a different letter differ at the 0.05 probability level according to Tukey's honestly significant difference (HSD). Numbers within parentheses are standard error (SE) of the means.

The effect of the interaction between treatment and depth was significant for some of the soil properties. This included the gravimetric moisture content, which had significantly higher means under each of the deep chiseling × deeper depth and shallow chiseling × deeper depth, than those under the remainder of the combinations of treatment and depth. A similar effect of this interaction was recorded for the available water capacity, with the deep chiseling × shallower depth being midway between the combinations of deep chiseling × deeper depth and shallow chiseling × deeper depth above it, and the remainder of the combinations of treatment and depth below it. This interaction was also significant for the bacterial relative abundance, which followed the trend of deep chiseling × shallower depth > shallow chiseling × shallower depth > the remainder of the combinations of treatment and depth (Table 3). To some extent, this interaction demonstrates the overall positive relations between the physical and biotic properties, which determine the soil quality.

Table 3. Effect of the interaction treatment × depth on the gravimetric moisture content (Θ_g: %), available water capacity (AWC: mm water per 5-cm soil layer), and bacterial relative abundance (16S rDNA fragment number g^{-1}).

	P Value	Deep Chiseling × 0–5 cm	Deep Chiseling × 15–20 cm	Shallow Chiseling × 0–5 cm	Shallow Chiseling × 15–20 cm	Control × 0–5 cm	Control × 15–20 cm
Θ_g	**<0.0001**	3.1 b (0.1)	8.5 a (0.6)	3.3 b (0.2)	7.2 a (0.6)	2.9 b (0.2)	3.6 b (0.3)
AWC	**0.0056**	6.2 ab (0.4)	8.3 a (0.8)	5.5 b (0.4)	7.9 a (0.6)	5.7 b (0.3)	4.9 b (0.6)
Bacterial relative abundance	**0.0016**	1.07×10^8 a (9.94×10^6)	1.34×10^7 c (1.42×10^6)	6.25×10^7 b (5.27×10^6)	8.84×10^6 c (1.53×10^6)	2.76×10^7 c (3.67×10^6)	6.97×10^6 c (3.90×10^5)

Notes: Bold *P* value indicates a significant effect. Means within a row followed by a different letter differ at the 0.05 probability level according to Tukey's honestly significant difference (HSD). Numbers within parentheses are standard error (SE) of the means. Only significant interactions are presented.

3.3. General Discussion and Implications

It is proposed that over time, the above- and below-ground processes foster each other through mutual feedback loops. The main generators of these feedbacks in the severely degraded and compacted lands are the breaking of the mechanical crust cover, increase in roughness of the ground surface, and the greater aeration of soil. For a schematic illustration of these feedbacks, see Figure 3.

In the deep chiseling plots, the high intensity of surface roughness induced by the tillage action [51], allows the retention of a large amount of raindrops. This water includes both drops falling on-site, as well as drops falling off-site, running on the ground surface, and harvested by the surface micro-topography [52]. Simultaneously, the intensive surface roughness allows the trapping of fine mineral materials and off-site originated organic residues and seeds, which get deposited on-site [53]. Coupled with the breaking of the mechanical crust cover, the trapped mineral materials make the surface more porous, easing water infiltrability. The trapped organic residues shade the ground surface and decrease soil-water loss through evaporation [54], while the trapped seeds become available for germination on-site [29,30]. Water infiltration is accelerated by the intensive aeration of soil, which is induced by the deep chiseling action [55]. The high infiltration rate and decreased evaporation loss increase the availability of water for plant-use [56]. Simultaneously, the high infiltration rates and decreased evaporation loss, increase the leaching of calcium carbonate [57], and stimulate microbial activity [48]. The latter enables high cycling rates of nutrients [49], which become available for plant uptake [58]. Over time, the establishment of vegetation accelerates the trapping of fine mineral materials [59] and organic residues originating off-site [60]. Also, the on-site developed vegetation becomes a source for additional organic residues and seeds [61]. Moreover, the established vegetation shades the ground surface underneath its canopy, further reducing soil-water loss through evaporation [62]. At the same time, the vegetation growth results in the loss of soil-water through transpiration [63]. One way or another, both the deposited and defoliated organic residues become a source for the soil organic carbon pool [64]. The latter increases macro-aggregate formation and stability [65] resulting in better aeration, greater available water capacity [66], and faster root development. These three effects further strengthen the microbial activity, pedogenesis, and vegetation growth [62,66], accelerating the entire chain of geo-ecological feedbacks (Figure 3a). In the shallow chiseling plots, the same feedbacks take place, though to a smaller magnitude, which is determined by the mid-intensity of surface roughness, coupled by the aeration of only a medium soil depth (Figure 3b).

In the no-tillage, control plots, the surface smoothness limits the deposition of fine mineral materials and organic residues and seeds originating off-site [59]. Also, the surface smoothness hinders the on-site retention of raindrops. Coupled with the compaction-induced limited soil aeration [55] and diminished water infiltrability [67], these processes cause the generation of intensive runoff of water [68]. Further, the low infiltrability of water diminishes leaching of calcium carbonate [57], and hinders microbial activity [58]. The no deposition of organic residues allows high evaporation rates [54], and enables no input of organic matter to the soil organic pool, with the resultant small macro-aggregate formation, and low available water capacity [62,66]. The combined effects of these processes allow no germination and establishment of plants, with the resulting retardation of self-restoration processes (Figure 3c).

Overall, results of this study conform to those of previous studies, which showed that under severely degraded lands, self-restoration processes are hindered [69–71]. Such conditions negate the effectiveness of passive restoration means, and necessitate active intervention means for commencing restoration processes. Such intervention means are particularly relevant for drylands, where self-restoration processes are hindered by the limited water availability. Therefore, the obtained results support the study's main hypothesis. At the same time, the results do not completely confirm the study's secondary hypothesis. This is because even though the advantage of the deep chiseling treatment over the shallow chiseling treatment was apparent for the soil properties, it was not clearly noticeable for the spontaneously-established vegetation properties. This difference between the soil and vegetation responses is assumed to be affected by the greater sensitivity of pedogenic processes than by that of plant community, to tillage management practices. Yet, it is expected that over time, the above-described feedbacks between the soil and plants will be reflected in increasing differences in the vegetation parameters among the three studied treatments. Continuation of this study over a longer time span is therefore needed in order to verify this expectation. It is also necessary for similar studies to be conducted in degraded shrublands in other drylands across the world.

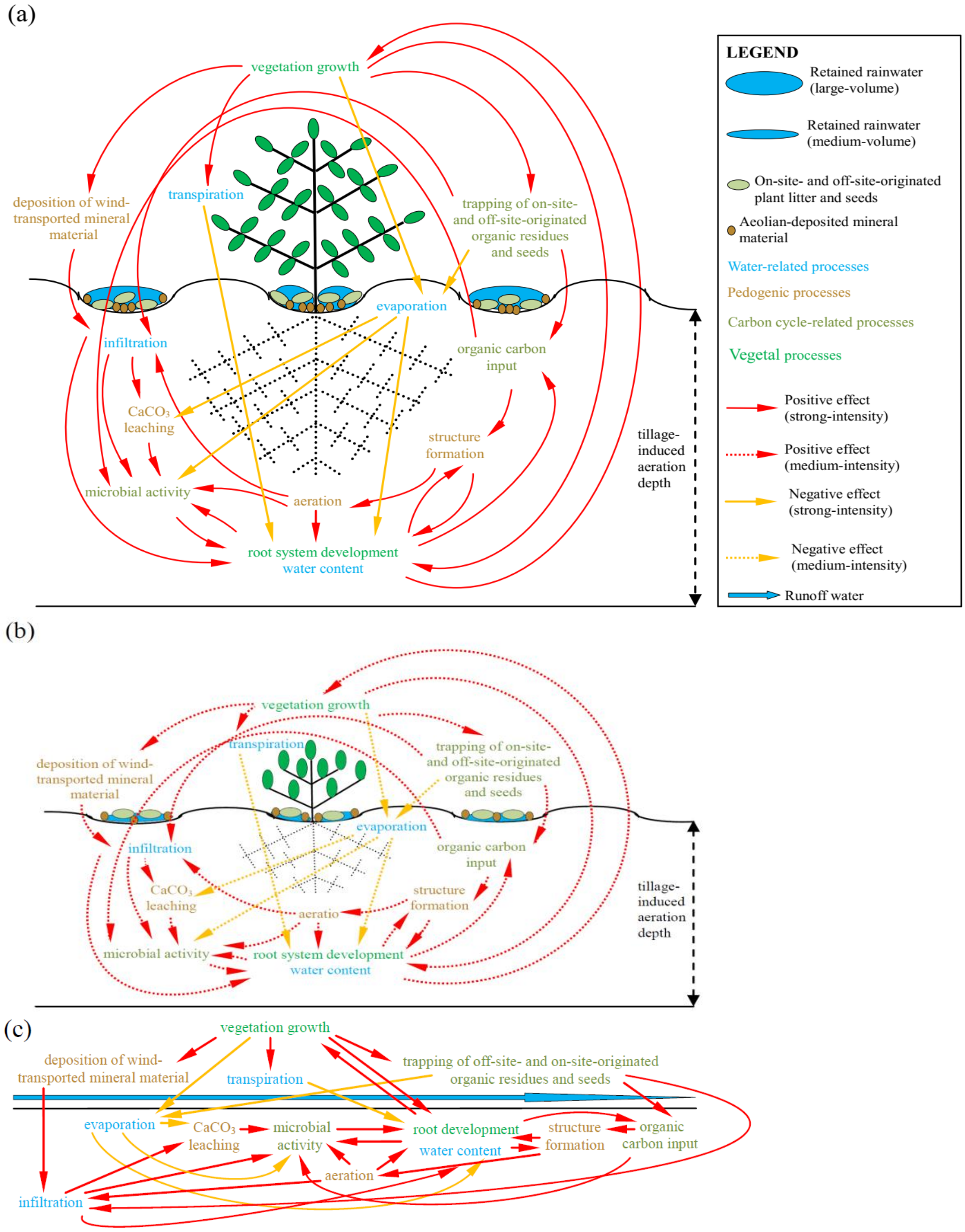


Figure 3. Schematic illustration of feedbacks among water-soil-plant-organic matter under deep chiseling (**a**); shallow chiseling (**b**); and no-tillage (**c**) of severely degraded lands. Deep tillage induces aeration at a deep soil layer and forms intense roughness of the ground surface, generating strong-intensity feedbacks among water-soil-plant-organic matter. Shallow tillage induces aeration at a shallow soil layer and forms medium roughness of the ground surface, generating medium-intensity feedbacks among water-soil-plant-organic matter. Strong feedbacks occur also in the no-tilled, severely degraded lands.

4. Conclusions

In this study, we assessed the use of a single chiseling session as a means for restoring severely degraded and compacted lands. Results of this study revealed that several parameters of spontaneously-established vegetation were generally better under the chiseling treatments than those under the no-tillage plots, but there were no clear and consistent differences between the deep and shallow chiseling treatments. At the same time, soil quality was best under the deep chiseling plots, moderate under the shallow chiseling plots, and worst under the no-tillage plots. It is concluded that the extreme degradation and compaction of soil in the no-tillage plots hinders self-restoration processes. This is particularly relevant for drylands, where limited water availability slows down such processes. Also, it is foreseen that, considering the continued exclusion of any kind of anthropogenic disturbances, the differences among the three treatments will increase over time.

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Appendix A

Figure A1. Research block, with deep chiseling treatment plot on the right side, shallow chiseling treatment plot on the left side, and a control plot in the middle. Note the greatest surface roughness on the right, intermediate roughness on the left, and smallest roughness in the middle. Photographed by I. Stavi in April 2017, three years after the plots were established.

Appendix B. Recorded Plant Species, by Year and Treatment.

Year	Treatment	Species	Year	Treatment	Species	Year	Treatment	Species
2015	Control	*Aizoon hispanicum*	2016	Control	*Aaronsohnia factorovsky*	2017	Control	*Atractylis sp.*
		Anabasis articulata			*Aizoon hispanicum*			*Avena sp.*
		Anthemis sp.			*Andrachne telephioides*			*Erodium crassifolium*
		Arnebia decumbens			*Anthemis sp.*			*Gymnarrhena micrantha*
		Artemisia sieberi Besser			*Astragalus sp.*			*Haloxylon sp.*
		Astragalus hamosus			*Astragalus asterias Hohen*			*Malva aegyptia*
		Astragalus tribuloides Delile			*Astragalus hamosus*			*Neotorularia torulosa*
		Atriplex halimus			*Astragalus tribuloides Delile*			*Plantago crypsoides*
		Bassia arabica			*Atractylis phaeolepis Pomel*			*Plantago ovata*
		Bassia indica			*Avena wiestii*			*Reaumuria sp.*
		Calendula arvensis			*Calendula arvensis*			*Reichardia tingitana*
		Carduus argentatus			*Carduus argentatus*			*Schismus arabicus Nees*
		Carrichtera annua			*Centaurea sp.*			*Stipa capensis*
		Centaurea ammocyanus			*Centaurea ammocyanus*			*Trigonella stellata*
		Erodium crassifolium			*Erodium crassifolium*		Shallow tillage	*Aaronsohnia factorovsky*
		Erucaria rostrata			*Erucaria microcarpa*			*Anthemis sp.*
		Filago desertorum Pomel			*Filago desertorum Pomel*			*Arnebia decumbens*
		Gymnarrhena micrantha			*Gymnarrhena micrantha*			*Astragalus sp.*
		Haloxylon salicornicum			*Hordeum glaucum*			*Avena sp.*
		Haloxylon scoparium Pomel			*Lappula spinocarpos*			*Buglossoides tenuiflora*
		Lappula spinocarpos			*Leontodon laciniatus*			*Centaurea sp.*
		Leontodon laciniatus			*Malva aegyptia*			*Eremopyrum bonaepartis*
		Malva aegyptia			*Malva parviflora*			*Erodium crassifolium*
		Malva parviflora			*Medicago laciniata*			*Filago desertorum Pomel*
		Nasturtiopsis coronopifolia			*Nasturtiopsis coronopifolia*			*Gymnarrhena micrantha*
		Neotorularia torulosa			*Plantago sp.*			*Haloxylon sp.*
		Phalaris minor			*Pteranthus dichotomus*			*Malva aegyptia*
		Pteranthus dichotomus			*Reaumuria hirtella*			*Malva parviflora*
		Reaumuria hirtella			*Reichardia tingitana*			*Neotorularia torulosa*
		Reichardia tingitana			*Schismus arabicus Nees*			*Plantago crypsoides*
		Roemeria hybrida			*Scorzonera papposa*			*Plantago ovata*
		Salsola inermis			*Senecio glaucus*			*Pteranthus dichotomus*
		Schismus arabicus Nees			*Silene vivianii*			*Reaumuria sp.*
		Scorzonera papposa			*Stipa capensis*			*Reichardia tingitana*
		Silene decipiens			*Trigonella stellata*			*Salsola inermis*
		Spergula fallax		Shallow tillage	*Aaronsohnia factorovsky*			*Schismus arabicus Nees*

Year	Treatment	Species	Year	Treatment	Species	Year	Treatment	Species
		Spergularia diandra			*Anthemis sp.*			*Senecio glaucus*
		Stipa capensis			*Arnebia decumbens*			*Silene decipiens*
		Trigonella stellata			*Astragalus sp.*			*Stipa capensis*
		Vulpia myuros			*Astragalus asterias Hohen*			*Stipagrostis plumosa*
	Shallow tillage	*Allium rothii*			*Astragalus hamosus*			*Trigonella stellata*
		Anthemis sp.			*Astragalus tribuloides Delile*		Deep tillage	*Aaronsohnia factorovsky*
		Arnebia decumbens			*Avena wiestii*			*Anthemis sp.*
		Astragalus hamosus			*Calendula arvensis*			*Avena sp.*
		Astragalus tribuloides Delile			*Carduus argentatus*			*Erodium crassifolium*
		Atriplex halimus			*Erodium crassifolium*			*Gymnocarpos decander*
		Avena wiestii			*Erucaria microcarpa*			*Haloxylon sp.*
		Bassia arabica			*Gymnarrhena micrantha*			*Lappula spinocarpos*
		Bassia indica			*Hordeum glaucum*			*Malva aegyptia*
		Calendula arvensis			*Leontodon laciniatus*			*Nasturtiopsis coronopifolia*
		Centaurea ammocyanus			*Malva aegyptia*			*Neotorularia torulosa*
		Erodium crassifolium			*Malva parviflora*			*Plantago crypsoides*
		Erucaria rostrata			*Nasturtiopsis coronopifolia*			*Pteranthus dichotomus*
		Filago desertorum Pomel			*Pteranthus dichotomus*			*Reaumuria sp.*
		Gymnarrhena micrantha			*Reaumuria hirtella*			*Salsola inermis*
		Lappula spinocarpos			*Reichardia tingitana*			*Schismus arabicus Nees*
		Leontodon laciniatus			*Salsola inermis*			*Scorzonera papposa*
		Malva aegyptia			*Salsola inermis*			*Silene decipiens*
		Malva parviflora			*Schismus arabicus Nees*			*Stipa capensis*
		Nasturtiopsis coronopifolia			*Scorzonera papposa*			*Thymelaea hirsuta*
		Neotorularia torulosa			*Senecio glaucus*			*Trigonella stellata*
		Pteranthus dichotomus			*Silene vivianii*			
		Reaumuria hirtella			*Sonchus oleraceus*			
		Reichardia tingitana			*Stipa capensis*			
		Roemeria hybrida			*Trigonella stellata*			
		Salsola inermis			*Tulipa systola Stapf*			
		Salsola vermiculata		Deep tillage	*Aaronsohnia factorovsky*			
		Schismus arabicus Nees			*Aizoon hispanicum*			
		Scorzonera papposa			*Andrachne telephioides*			
		Silene colorata			*Anthemis sp.*			
		Spergula fallax			*Atriplex leucoclada*			
		Stipa capensis			*Avena wiestii*			
		Trigonella stellata			*Calendula arvensis*			
	Deep tillage	*Aegilops kotschyi*			*Carduus argentatus*			

Year	Treatment	Species	Year	Treatment	Species	Year	Treatment	Species
		Aizoon hispanicum			*Centaurea ammocyanus*			
		Anthemis sp.			*Erodium crassifolium*			
		Arnebia decumbens			*Erucaria microcarpa*			
		Astragalus asterias Hohen			*Filago desertorum Pomel*			
		Astragalus hamosus			*Gymnarrhena micrantha*			
		Astragalus tribuloides Delile			*Hordeum glaucum*			
		Avena wiestii			*Launaea sp.*			
		Bassia arabica			*Leontodon laciniatus*			
		Calendula arvensis			*Malva aegyptia*			
		Carduus argentatus			*Malva parviflora*			
		Centaurea ammocyanus			*Medicago laciniata*			
		Eremopyrum bonaepartis			*Nasturtiopsis coronopifolia*			
		Erodium crassifolium			*Pteranthus dichotomus*			
		Erucaria rostrata			*Reaumuria hirtella*			
		Filago desertorum Pomel			*Reichardia tingitana*			
		Filago pyramidata			*Salsola inermis*			
		Gymnarrhena micrantha			*Schismus arabicus Nees*			
		Hordeum glaucum			*Scorzonera papposa*			
		Ifloga spicata			*Senecio glaucus*			
		Lappula spinocarpos			*Sonchus oleraceus*			
		Leontodon laciniatus			*Spergula fallax*			
		Malva aegyptia			*Stipa capensis*			
		Malva parviflora			*Trigonella arabica Delile*			
		Nasturtiopsis coronopifolia			*Trigonella stellata*			
		Neotorularia torulosa						
		Pteranthus dichotomus						
		Reaumuria hirtella						
		Reichardia tingitana						
		Roemeria hybrida						
		Salsola inermis						
		Salsola tragus						
		Schismus arabicus Nees						
		Scorzonera papposa						
		Silene colorata						
		Silene decipiens						
		Sonchus oleraceus						
		Spergula fallax						
		Spergularia diandra						
		Stipa capensis						
		Trigonella stellata						

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