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Properties, challenges, and opportunities of the loess plains in the northern Negev Desert: A review

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Abstract: The loess plains cover approximately 2000.00 km² of the northern Negev Desert, accounting for about 9% of Israel's total land area. As elsewhere, the loess in the Negev Desert is composed of wind-transported dust and sand particles that have been deposited in sink sites. The loess deposits are characteristically covered by biocrusts, which constitute a substantial share of the region's primary productivity. The biocrusts regulate the vascular vegetation communities, including herbaceous and woody plants, many of which are endemic and/or endangered plant species. Throughout history, the region's main land-uses have been based on extensive livestock grazing and runoff-harvesting agriculture, which both still exist to some extent. These land-uses did not challenge the sustainability of the geo-ecosystems over centuries and millennia. At present, predominant land-uses include intensive rangelands (1016.81 km², encompassing 51% of the loess plains' area), croplands (encompassing both rainfed and irrigated cropping systems: 930.92 km², 47% of the loess plains' area), and afforestation lands (158.75 km²). These current land-uses impose substantial challenges to the functioning of the loess plains. Further, urban and rural settlements have expanded considerably in the last decades (158.45 km²), accompanied by mass construction of infrastructures. Altogether, these new land-uses have caused widespread soil erosion, soil structure deformation, depletion of soil organic carbon, environmental contamination, native vegetation removal, invasion of plant species, and habitat fragmentation. Recent climate change has intensified these stressors, exacerbating adverse impacts and forming feedback loops that intensify land degradation and desertification. The declining ecosystem functioning over recent decades emphasizes the urgent need for passive and active restoration schemes. While some of these efforts have proven to be successful, other have failed. Therefore, proactive policy making and environmental legislation are needed to plan and develop schemes aimed at halting land degradation, while simultaneously maximizing nature conservation and restoration of degraded lands across the loess plains. Such actions are expected to increase the regions' capacity for climate change mitigation and adaptation.

Keywords: biocrusts; climate change; desertification; land degradation; land-use and land-use change (LULUC); loess plains; Negev Desert

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1 Introduction

Loess, an aeolic deposit of the Quaternary (2.6×10^{6} a to present), originated both in warm drylands (Li et al., 2020a) and cold/icy regions (Li et al., 2020b). Glacial loess forms in

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mountainous or other continental landforms as glaciers grind the underlying bedrocks. In North America, the major sources of loess are continental sites such as the Quaternary Laurentide Ice Sheet in eastern Canada, as well as mountainous sites such as the Rockies in central United States. In Europe, the major sources are the Quaternary Fennoscandian Ice Sheet in the continent's north and the Carpathians. Non-glacial loess forms in dryland regions, such as the Gobi and Tianshan Mountains in Central Asia, the Kalahari in Southern Africa, and the Sahara in North Africa (Li et al., 2020b). Loess derived from volcanic eruptions can be found in South America, Alaska, Iceland, and New Zealand (e.g., Cowie, 1964). As such, non-glacial loess describes loess deposits formed by mechanisms such as freeze-thaw weathering cycles, salinization, solar irradiation-related deformation processes, biological degradation, etc. (Li et al., 2020b). Loess deposits cover approximately 4% of the world's terrestrial area (Börker et al., 2020), and record information on climatic, atmospheric, and sedimentary changes over tens and hundreds of millennia (Avni et al., 2015).

In granulometric terms, the predominant size fractions of loess particles are silt (2–63 μm) and very fine sand (63–125 μm) (Crouvi et al., 2010; Börker et al., 2020). Yet, the mechanical composition can range between finer and coarser textures, and is determined by the features of the source material, transportation distance, properties of the depositional site (Li et al., 2020b), and whether sand particles are braded to smaller particles (Crouvi et al., 2010). Relatively large sand particles are transported through aeolian saltation at low heights over the ground surface and deposited near the source. Smaller silt particles are transported at intermediate heights and deposited in sink sites that are farther from the source. The smallest particles are easily transported at greater heights than dust, and travel the farthest distances. Once deposited, particles may be transported by overland flow in continuously flowing mountainous rivers, or by flashfloods in ephemeral streambeds in drylands. Either way, fluvial processes can transport large quantities of mineral materials from source areas at high elevations to lower depositional sites (Li et al., 2020b).

Over time, surface processes may trigger pedogenic-like processes in loess deposits, forming a surface horizon (A) (Finke et al., 2013). In the sub-surface (B), vertical processes of eluviation (E) and illuviation (Bt) of dissolved and suspended minerals may take place (Muhs, 2007). Moreover, stratification may form additional horizons such as the transition zone (BC), decalcified loess material (C1), and undisturbed calcareous loess material (C2) at deeper depths (Vanwalleghem et al., 2010). It has been proposed that loess profile genesis is dependent on the distance from the source area, and is positively strengthened windward (Ruhe, 1969). The mineralogy of loess deposits varies greatly, and can consist of quartz, feldspar, mica, and clay minerals. Because loess is rich in carbonates, it is highly alkaline. Over geological timespans, changes in the rate of loess weathering have substantial geochemical impacts (Börker et al., 2020). The Chinese Loess Plateau is the most expansive loess region worldwide (Li et al., 2020a). Additional expansive loess regions are found in Alaska, central United States, Central Europe, and Central Asia (Li et al., 2020b).

The loess plains of Israel have been thoroughly studied, covering a wide range of topics such as genesis (e.g., Crouvi et al., 2008, 2009), distribution (e.g., Shapiro, 2006; Avni et al., 2015), land-use and land-use change (LULUC) (e.g., Portnov and Safriel, 2004; Bruins and van der Plicht, 2017; Leu et al., 2021), and threats (e.g., Rotem et al., 2017; Rafaeli et al., 2023; Raveh-Amit et al., 2024). Yet, a comprehensive summary of these issues, alongside complementary environmental and sustainability aspects, is still missing. Therefore, the objectives of this article are to: (1) demonstrate the specific properties of the Negev Desert's loess materials and loess plains; (2) highlight the importance of biocrusts in determining biogeochemical cycles, including the interrelations between biocrusts and vascular vegetation communities; (3) describe ancient land-uses; (4) peruse current land-uses; (5) discuss the impacts of climate change; (5) determine the effects of settlements and other infrastructures; and (6) survey passive and active restoration schemes across the region.

2 Distribution and properties of loess in the Negev Desert

The distant source areas of the Negev Desert's loess are the northern margins of the Sahara and the Arabian Peninsula, from which fine particles (clay and fine silt) were transported over thousands of kilometers by cyclonic winds. The close source areas are the Wadi El-Arish and Sinai Peninsula sand dunes, as well as the Mediterranean Shelf, from which medium particles (coarse silt and fine sand) were transported (Crouvi et al., 2009). The Negev Desert's loess deposits evolved gradually. First, aeolian deposits were evenly distributed over the ground surface. Next, the loess was redistributed by local hydrological systems, where particles from high altitudes eroded and were transported to low altitudes (Avni et al., 2015).

In granulometric terms, the Negev Desert's loess is bi-modal, encompassing two size fractions (3–8 and 50–60 µm) (Crouvi et al., 2008). Loess of the Negev Desert is characteristically more saline than loess of Central Asia. It has been proposed that the loess deposited across the Negev Desert had no inherited salinity, but saline materials originating from the Mediterranean coastline accumulated later through aeolian deposition. As precipitation leaches salts, the decreasing precipitation gradient from northwest to southeast corresponds to an increasing salinity of loess deposits from north to south. The high aridity in the Negev Desert, compared to Central Asia, limits biological activity in the upper horizons of the loess profile and negates the formation of an organic horizon (Ao or A1) (Shapiro, 2006). The loess areas cover approximately 5500.00 km^2 across the northern and central Negev Desert (Crouvi et al., 2009). The loess plains (31°15′N, 34°45′E), at the northern edge of this area, extend over approximately 2000.00 km^2 (about 9% of Israel's land area; Fig. 1) between the Judean Lowlands to the north and the Negev Highlands to the south, and between the Dimona-Arad to the east and the Gaza coastline to the west (Rotem et al., 2017).

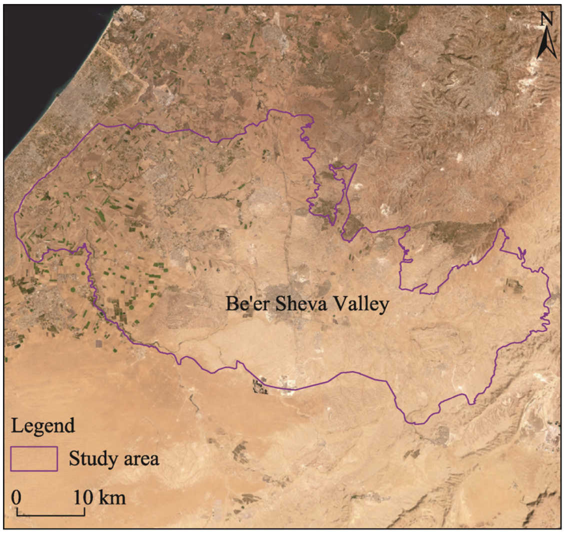


Fig. 1 Overview of the study area

The loess deposits have been dated through stratigraphic or archaeologic attribution, as well as by assessing ^{14}C radioactive isotopes in calcic nodules. Loess was deposited in the Negev Desert during the late Middle Pleistocene (approximately 0.18×10^6–0.13×10^6 before present) and Late Pleistocene (approximately 0.13×10^6–0.01×10^6 before present). A study on the evolution of the Negev Desert's loess deposits showed that in these ancient times, loess accumulated at a rate of approximately 0.2 mm annually (Crouvi et al., 2009). Yet, a recent study showed that the evolution of loess deposits is not unidirectional (Shalom et al., 2020). It was revealed that at present, secondary erosional-depositional processes occur, in which windstorms detach particles from loess deposits, transporting and depositing them in new sites. Further, a substantial share of local loess materials encompasses particles that have been deposited over the Negev Desert in modern times. Additionally, loess deposits are prone to water erosion, which transports loess particles and deposits them in new sites (Stavi et al., 2010).

Throughout the recent millennia, changes in loess deposition rates have led to periods of aggradation vs. depletion of loess deposits across the region. Visual evidence for depletion includes the alluvial terraces that are widespread throughout the loess deposits. Concordant with the topographic relief, the thickness of loess deposits ranges from a few millimeters to several meters (Avni et al., 2015). As elsewhere, pedogenic-like processes in the loess deposits of the northern Negev Desert form horizons throughout its profile (Rognon et al., 1987). Three types of loess, classified by visual and pedogenetic traits, are found throughout the northern Negev Desert. The first type consisting of brownish-yellowish materials has a developed profile with sandy to loamy sand texture, and is prevalent in the deep soils of Be'er Sheva Valley and Arad Valley, as well as in the western Negev Desert. The second type consisting of pale brownish-yellowish materials has an unclear profile with loamy sand to loamy texture, and is found in fluvially active depressions and in the Ruhama and Be'eri Badlands. The third type consisting of pale brown materials has a developed profile with sandy loam texture, and is found in hillslopes. These three loess types provide habitats for highly heterogeneous vegetation communities and diverse ecosystems in the Negev Desert (Dan, 1984; Perelberg and Ron, 2014).

3 Biocrusts and vascular plant communities

In drylands, water availability is the major limiting factor of primary productivity and biogeochemical processes (Young et al., 2021). Like soils, the biotic cover of loess deposits—including biocrusts and vascular vegetation—has a substantial impact on the redistribution of surface water, as well as on soil-water dynamics. In turn, through feedback loops, these variables determine the cover and dynamics of biocrusts and vascular plants (Zhang et al., 2022). In addition to the water cycle, these feedbacks regulate additional biogeochemical cycles, including carbon (C), nitrogen (N), etc. (Young et al., 2021; Zhang et al., 2022). While biocrusts improve the sequestration of organic C in the uppermost horizon of loess deposits, they increase soil respiration, thus augmenting carbon dioxide (CO_2) emissions. Yet, through photosynthesis, biocrusts increase the soil C pool, lowering atmospheric CO_2 concentrations and mitigating climate change (Dou et al., 2022).

Biocrusts are widespread in drylands, where their evolutionary properties, particularly high resilience to extreme aridity, have an advantage over other lifeforms (Tian et al., 2023). In the northern Negev Desert and in the other loess regions, cyanobacteria, lichen, and moss are the main components of biocrusts (Veste et al., 2001). It has been reported that different combinations of microbial components in biocrusts affect soil-water dynamics by determining sorptivity and infiltrability, thus dictating soil-water content and water overland flow (Eldridge et al., 2000). Additionally, as biocrusts control the temperature of the underlying soil (Qiu et al., 2024), they may either increase or decrease the evaporation rate of soil water (Kidron et al., 2022), thus regulating the ecosystem's water budget (Kidron et al., 2022; Qiu et al., 2024). Further, by increasing the cohesion among the soil particles and providing physical protection against exterior forces (Gao et al., 2020), biocrusts control the detachment of mineral particles from the ground surface through wind or water erosional processes (Veste et al., 2001).

Overall, the combined cover of biocrusts and vascular plants has a substantial impact on geo-ecosystem functions and services, mostly by regulating water infiltration, generating overland flow, and controlling soil erosion (Maestre et al., 2021). Therefore, biocrusts are considered ecosystem engineers in dryland environments (Veste et al., 2001). Specifically, the biocrusts' composition determines the germination, establishment, and growth of vascular plants, and thus regulates the plant community's structure and composition (Maggioli et al., 2022). Generally, the northern Negev Desert is defined as a xeric scrubland, where major vegetation lifeforms include therophytes (annual herbaceous plants), hemicryptophytes (perennial herbaceous plants), geophytes (bulb and tuber plants), dwarf shrubs (chamaephytes), and shrubs (phanerophytes) (Evenari et al., 1982). The composition, distribution, and patterns of these lifeforms, as well as their co-existence with biocrusts, indicate the level of geo-ecosystem functioning (Maestre et al., 2021).

The main plant communities across the loess plains are *Haloxylon scoparium* Pomel (syn. *Hammada scoparia* Pomel) community, *Anabasis articulata* (Forssk.) Moq. community, *Anabasis syriaca* Iljin community, *Zygophyllum dumosum* Boiss. community, and *Artemisia herba-alba* Asso subsp. *herba-alba* (syn. *Artemisia sieberi* Besser)–*Noaea mucronata* (Forssk.) Asch. & Schweinf. community (Gil et al., 2022). Additional predominant woody plant species are *Retama raetam* (Forssk.) Webb, *Thymelaea hirsuta* (L.) Endl., and *Achillea fragrantissima* (Forssk.) Sch.Bip. (Zohary, 1980). The region hosts many rare species, some of which are endemic at the local or national level, and may be considered as endangered species: the therophytes *Adonis aestivalis* L., *Astragalus trimestris* L., *Astragalus guttatus* Banks & Sol., *Reseda luteola* L., *Silene tridentata* Desf., *Reichardia intermedia* (Sch.Bip.) Coutinho, and *Galium philistaeum* Boiss.; the hemicryptophytes *Centaurea ascalonica* Bornm., *Pimpinella corymbosa* Boiss., *Vinca herbacea* Waldst. & Kit., and *Gypsophila pilosa* Huds.; and the geophytes *Leopoldia eburnea* Eig & Feinbrun, *Allium aschersonianum* Barbey, *Allium kollmannianum* Brullo, Pavone & Salmeri, *Allium qasyunense* Mouterde, *Iris atrofusca* Baker, and *Fritillaria persica* L. subsp. *arabica* (Perelberg and Ron, 2014; Rotem et al., 2017).

4 Historical land-uses

Throughout history, the most widespread use of the loess plains was for livestock grazing. Stratigraphic evidence for grazing has been recorded for the Late Neolithic period (7000–4500 Before Current Era (BCE)), Late Bronze Age (1550–500 BCE), Early Iron Age (1200–500 BCE), the Roman period (63 BCE–324 Common Era (CE)), and the early Islamic period (638–1099 CE) (Bruins and van der Plicht, 2017). Despite many exceptions, the more xeric southern and eastern edges of the loess plains in the northern Negev Desert have been grazed upon by camels, while the more mesic northern and western edges of the loess plains have been grazed upon by small ruminants (Degen, 2007).

Throughout the region, a wealth of archaeological remains indicates that agriculture was prevalent during ancient times. Typical agricultural structures encompass remains of terraces and stone walls in wadis (ephemeral stream channels) of different orders (Bruins and van der Plicht, 2017). Most remains have been discovered near Roman-Byzantine settlements (Avni et al., 2013). The terraces and walls were constructed to harvest runoff water, which drained to agricultural plots from hillslopes and dry channels in the watersheds' upstream sections (Evenari et al., 1982). In some sites, scattered small mounds of stones (*tuleilat el-anab*) covering hillslopes were discovered near the terraced wadis, with the aim of maximizing the alluvial runoff ratio (Lavee et al., 1997). While most of the runoff harvesting systems were used to produce cereals (Avni et al., 2013), a small share was utilized to grow fruit trees (Ashkenazi et al., 2020). In the cereal-cropping plots, livestock grazed on the stubble after harvest. In drought years, when seeds were not sown or grains did not ripen, livestock animals grazed on the native herbaceous vegetation or the aboveground biomass of partially-developed crops, demonstrating evidence for mixed land-uses across the region (Bailey, 2006).

In agronomic terms, it was suggested that runoff harvesting systems were effective over a certain historical time window, during which the thickness of deposited materials in the terraced plots was in balance with the rocky cover of hillslopes that maximized the runoff ratio (Avni et al., 2006). It has also been proposed that land abandonment and the consequent deterioration of terraces have exacerbated soil erosion, accelerating structural collapse and land degradation (Stavi et al., 2019a). Remains of terraces are widespread across the northern Negev Desert, most of which have been dated to the Islamic (638–1515 CE) and Ottoman (1516–1917 CE) periods (Stavi et al., 2024).

Although remains of runoff harvesting systems are widespread, it seems that grain production using these systems could have only supported a limited human population (Evenari et al., 1961). Thus, during more populated periods, the local communities could not have solely relied on local grain production, but must have imported grains and other food products (Rosen, 2019). As such, common land-uses, operated at intermediate rates, could have sustainably coexisted with the natural geo-ecosystems without imposing extensive pressures on the environment (Evenari et al., 1982). Regardless, it was proposed that the use of runoff harvesting systems was co-determined by the prevailing climatic conditions and geopolitical settings. Hence, alongside sufficient precipitations for supporting agricultural crop productivity (Bruins, 2012), administrative stability was necessary to provide security for the inhabitants of peripheral regions. Recent findings from the northern Negev Desert revealed a wealth of runoff harvesting agricultural systems that were used by the local Bedouin populations until the mid-20th century (Stavi et al., 2024).

Visual observations indicate that some ancient terraced lands are currently cultivated in parts of the loess plains. Yet, recurring crop failures during the last decades suggest that the aim of this land-use is to demonstrate historical affinity to the land rather than to produce grains (Marx and Meir, 2005). One way or another, in ecological terms, the agricultural plots that are presently cultivated using traditional/low-impact practices act as refugia for specialist plant species, some of which are rare: for example, therophytes such as *A. aestivalis* and *Glaucium arabicum* Fresen.; hemicryptophytes such as *Achillea wilhelmsii* K.Koch; and geophytes such as *Colchicum ritchii* R.Br., *Leopoldia longipes* (Boiss.) Losinsk., *Bellevalia eigii* Feinbrun, *Leontice leontopetalum* L., and *Anemone coronaria* L. These plant species emphasize the need to preserve these traditional cropping systems (Perelberg and Ron, 2014).

5 Current land-uses

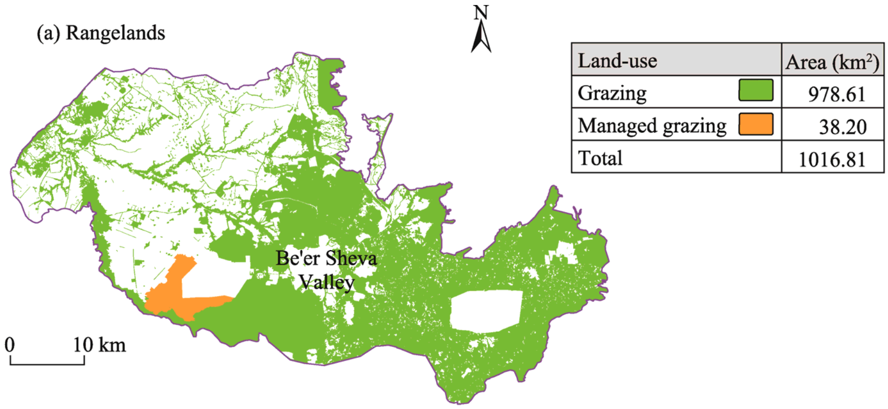
At present, several land-uses are prevalent across the northern Negev Desert, with some being extensive and others characterized by higher intensity of use. These land-uses are discussed below, in ascending intensity.

The most expansive land-use encompasses grazing by livestock animals, mostly sheep and goats held by the local Bedouin communities (Degen, 2007). Rangelands cover 1016.81 km^2 of the loess plains, encompassing 51% of its area (Fig. 2a). The region's livestock sector encompasses approximately 7.50×10^4 animals, divided among about 300 herds (Kababya, 2022). Most of the sector is regulated by the Ministry of Agriculture and Rural Development (2023). Predominantly, the region's eastern and southern edges are prone to heavy grazing pressures. Like other drylands worldwide, in addition to the climatic factors, the herd size, grazing duration, and grazing season primarily determine the spatiotemporal changes in the rangelands' net primary productivity (NPP) and functioning (Pringle and Landsberg, 2004).

It seems that apart from extremely rainy years, the overall NPP has been relatively meager in recent years. As such, forage productivity has typically been too low to support the region's herds; thus, herds are taken to graze in the northern Judean Plains, while herders increasingly rely on purchased supplementary feed (Shkolnik et al., 1980). One way or another, irrational grazing has led to deterioration in geo-ecosystem functioning, exemplified by a decrease in cover, richness, and diversity of vegetation communities, alongside degraded soil quality and accelerated soil erosion processes (Portnov and Safriel, 2004). In some parts of the region, grazing mismanagement has led to the expansion of non-palatable plants, such as *Asphodelus ramosus* L. (Perelberg and Ron, 2014). In addition to open lands, livestock grazing has also been managed in afforestation lands (Landau et al., 2015) and croplands (Stavi et al., 2015). The camel sub-sector encompasses an important role among the region's Bedouin communities. In 2008, this sub-sector numbered 0.30×10^4–0.50×10^4 animals, which supported the livelihood of approximately 300 families. Yet, camels, which have been perceived as destructive to natural ecosystems, are not supported by the Ministry of Agriculture and Rural Development and have not been allocated seasonal grazing lands. As such, they are forced to graze in lands allocated for small ruminants, exceeding the lands' carrying capacity and accelerating land degradation (Natan, 2008).

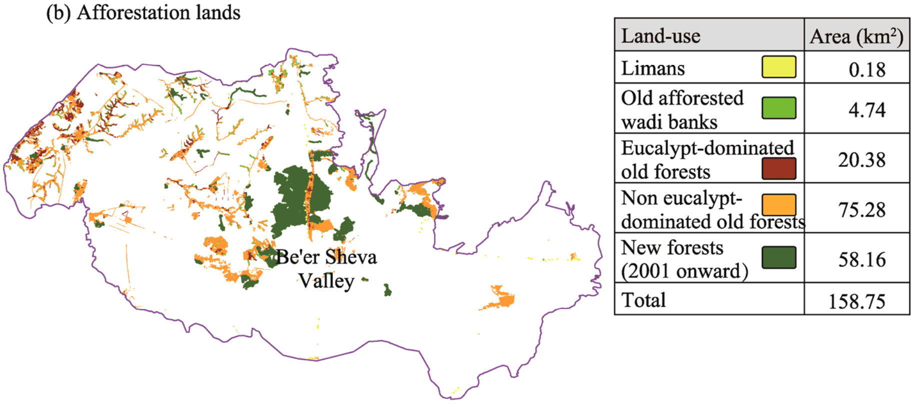
Afforestation in designated lands, wadi banks, and cropland margins has been implemented with monoculture or polyculture planting regime. As elsewhere, the monoculture forests have experienced serious challenges, such as degraded biodiversity and deteriorated geo-ecosystem health (Tal and Gurion, 2009). Across the northern Negev Desert, the monoculture forests have been planted at relatively high density and have not necessarily relied on runoff harvesting. However, the polyculture forests have been designed as 'savannization' systems, which are comparatively sparse and depend on runoff harvesting (Ritz Finkelstein, 2014). In wadi banks and cropland margins, the rate of pre-afforestation intervention is relatively low, whereas in designated afforestation lands, earthworks are widely implemented to reshape the landscape.

(a) Rangelands



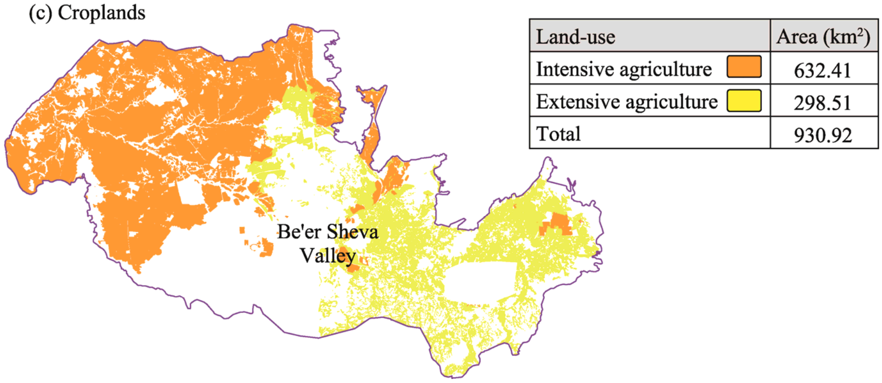
Land-use		Area (km^2)
Grazing	🟩	978.61
Managed grazing	🟧	38.20
Total		1016.81

(b) Afforestation lands



Land-use		Area (km^2)
Limans	🟨	0.18
Old afforested wadi banks	🟩	4.74
Eucalypt-dominated old forests	🟥	20.38
Non eucalypt-dominated old forests	🟧	75.28
New forests (2001 onward)	🟩	58.16
Total		158.75

(c) Croplands



Land-use		Area (km^2)
Intensive agriculture	🟧	632.41
Extensive agriculture	🟨	298.51
Total		930.92

Fig. 2 Distribution of rangelands (a), afforestation lands (b), and croplands (c) across the loess plains. These figures were produced based on open data obtained from https://deshe.org.il.

In wadis, earthworks are aimed at establishing limans to control fluvial connectivity (Brand et al., 2015). In hillslopes, earthworks are mostly aimed at forming contour bench terraces that disconnect alluvial processes (Wilson, 1980; Brand et al., 2015). While some of these projects have proved to be effective, the success of many of the region's afforestation lands is still questionable. Specifically, earthworks remove the soil's A-horizon to form the earth structures and eliminate ground surface roughness in the runoff-contributing areas. It has been reported that this action reduces coverage and diversity of plant community and degrades ecosystems (Rotem et al., 2013). Nevertheless, some of the afforested lands have experienced mixed land-uses, such as livestock grazing, which is generally managed to prevent overgrazing (Ritz Finkelstein, 2014; Brand et al., 2015). Regardless, the forestry agencies' past tendency to plant exotic tree species, some of which are invasive—such as the *Acacia saligna* (Labill.) H.L.Wendl. and various *Prosopis* spp.—may degrade the diversity of native vegetation communities (Portnov and Safriel, 2004), and endanger additional functions and services of these systems (Rotem et al., 2013). Overall, afforestation lands in the loess plains cover 158.75 km^2 (Fig. 2b).

Rainfed agriculture has been existed over expansive lands across the loess plains, primarily for cultivating wheat and barley (Lomas, 1984). In geo-ecological terms, the most impactful management practice is tillage, although it is usually implemented at relatively shallow depths (5–10 cm). As elsewhere, this practice breaks macroaggregates, deforms soil structure, and accelerates soil erosion (Stavi and Lal, 2011). Additionally, it increases the oxidation of organic C from the soil, emitting substantial amounts of CO_2 greenhouse gas to the atmosphere (Zapata et al., 2021). It seems that these adverse effects can be mitigated through no-till management and other reduced-tillage systems (Bonfil et al., 1999). In most years, low grain yields across extensive rainfed croplands in the region do not justify harvest. Often, the NPP of a substantial share of these lands is even too low to justify grazing. Yet, in comparatively rainy years, moderate grazing of the stubble after harvest may improve the functioning of these mixed-use lands (Stavi et al., 2015). In ecological terms, it was shown that rainfed agriculture has caused the destruction of habitats across the region (Perelberg and Ron, 2014).

Irrigated agriculture is practiced in expansive drylands of the western loess plains. Vegetables, predominantly potatoes, along plantations of jojoba (Benzioni et al., 2005), olives (Katuri et al., 2019), and citrus (Efron et al., 2001), are cultivated as major crops. As elsewhere, the vegetable cropping systems require deep tillage (15–25 cm depth), alongside intensive pest control and nutrient management, whereas plantations require intensive pre-planting preparation practices, as well as pest management and frequent fertilizing (USAID, 1988). All crops rely on irrigation water from various sources and of varying quality levels, some of which degrade soil functions (Katuri et al., 2019). It was reported that the use of chemical fertilizers, herbicides, pesticides, and treated wastewater has polluted and salinized soils in expansive croplands regionwide (Perelberg and Ron, 2014). Further, as elsewhere, the heavy reliance on N fertilizer causes substantial emissions of nitrous oxide (N_2O) greenhouse gas (Qiu et al., 2020). These adverse impacts may be alleviated by conservation agricultural practices, such as the application of manures and composts (USAID, 1988). Regardless, monocultural vegetable or plantation systems increase the risk of pest infestation, consequently degrading agrosystem health (Portnov and Safriel, 2004; Katuri et al., 2019). Further, it has been reported that irrigated agriculture has caused the spread of opportunistic therophytes such as *Salsola tragus* L. (syn. *Kali tragus* (L.) Scop.), and of phanerophytes such as *Solanum incanum* L. and *Prosopis farcta* (Banks & Sol.) J.F.Macbr. (Zohary, 1980), as well as the invasion of therophytes such as *Verbesina encelioides* (Cav.) Benth. & Hook.f. ex A.Gray (Ben-Israel et al., 2012). Overall, croplands cover 930.92 km^2 across the loess plains, encompassing 47% of its area (Fig. 2c).

6 Climate change impact

Over the last decades, expansive areas across the Mediterranean Basin have been experiencing climate change, with a general trend of precipitation decrease (Golodets et al., 2015) coupled with increasing inter-annual rainfall variability, alongside consecutive drought years alternating with wet episodes (Deitch et al., 2017). Yet, current climate trends and future forecasts for the Negev Desert remain uncertain. Specifically, it has been reported that in the northern Negev Desert, temperatures are rising while extreme rainfall events and severe droughts are both becoming more frequently (Kafle and Bruins, 2009; Saaroni et al., 2012). Analyses of precipitation trends for the period 1975–2000 showed an increase in precipitation, but a shorter rainy season and fewer rainy days (Drori et al., 2021). Another study forecasted a reduced number of rainy days and less accumulated annual rainfall, alongside higher daily maximum and minimum temperatures and intensification of droughts over the coming decades (Yosef et al., 2019). Recent studies have shown that long-term droughts across the region limit soil-water storage, imposing substantial stresses on local ecosystems (Stavi et al., 2018a; Argaman et al., 2020).

In rangelands and other open lands, these trends have caused the mass mortality of shrubs, resulting in geo-ecosystem degradation and simplification. Yet, it has also been reported that this mass mortality—predominantly for *N. mucronata* shrubs—has been confined to homogeneous hillslopes, which are characterized by a thick and non-stony soil layer. Meanwhile, shrub mortality was insignificant in heterogeneous hillslopes, which are characterized by a thin, stony soil layer that overlays weathered bedrock (Stavi et al., 2018a, 2019b). The improved habitat conditions in the heterogeneous hillslopes, specifically, increased soil-water from micro-aquicludes found within the weathered bedrock (Stavi et al., 2018a) and higher soil quality (Stavi et al., 2019b) increase the shrubs' resilience to droughts and climate change (Stavi et al., 2018a). In afforestation lands planted with *Pinus halepensis* Mill., the increasing temperatures and decreasing precipitations have lowered seedling survival (Pozner et al., 2022), caused mass mortality of mature trees due to drying (Preisler et al., 2019), and reduced the trees' resistance to diseases and pests (Dubinin et al., 2024) such as bark beetles (Golan et al., 2022). Yet, similarly to rangelands, it was proposed that in afforestation lands, mass mortality of trees is less common in heterogeneous hillslopes with a substantial rocky ground cover and high stone content in the soil profile, which increase soil-water availability (Preisler et al., 2019). In croplands, climate change directly increases evaporation losses (Tal, 2016) and heat stress in some crops (Bonfil et al., 2018). As elsewhere, climate change can indirectly affect crops by exacerbating disease and pest infestations (Kashyap et al., 2023).

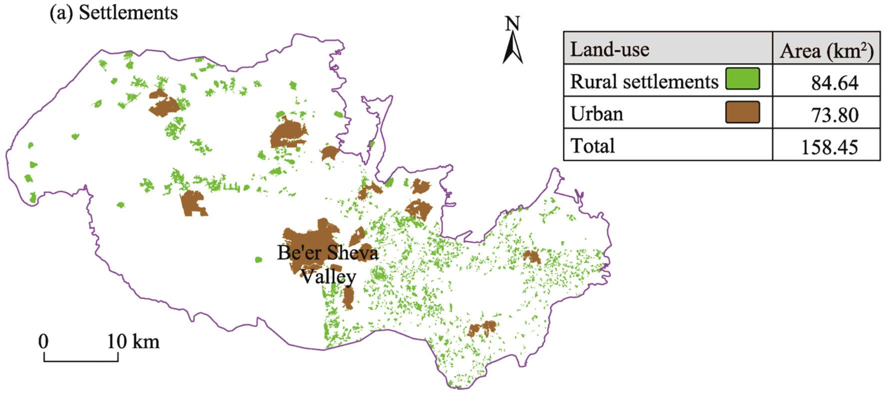
Under all land-uses, ground surface exposure due to vegetation mortality elevates soil temperatures and increases evaporation losses (Tang et al., 2023), exacerbates soil salinization and/or sodification (Tal, 2016; Stavi et al., 2019b; Pozner et al., 2022), and accelerates soil erosion (Granatstein, 1992) that is further aggravated by extreme rainstorms (Han et al., 2020). Yet, it is quite difficult to distinguish between 'natural' (i.e., climate) and anthropogenic (i.e., land-uses and management) impacts (Coppus, 2023), except for rare events in which land degradation is clearly caused by changing climatic/meteorological conditions (e.g., Stavi et al., 2010). One way or another, climate change aggravates land degradation and desertification processes that have been induced by irrational land-uses and mismanagement. Further, it seems that often, the 'natural' and anthropogenic factors strengthen each other through webs of feedback loops, which accelerate land degradation and desertification over time (Olsson et al., 2019).

Additionally, the transformation of 'natural' lands to rangelands, afforestation lands, or croplands (in ascending order of change intensity) simplifies geo-ecosystems (Riechers et al., 2020), consequently lowering pedodiversity (Ibáñez et al., 2014) and geodiversity (Vernham et al., 2023). Recent studies in the northern Negev Desert showed that climate change has reduced soil quality, degraded soil-water availability for vegetation, and decreased resilience of geo-ecosystems (Stavi et al., 2018a, 2019b). Studies conducted in other parts of the world indicate the negative relations between simplification of geo-ecosystems and their resistance to pests (e.g., Grab et al., 2018). In turn, frequency and intensity of pest infestations are expected to increase as a result of climate change, adversely affecting ecosystem health and functioning (Ministry of Environmental Protection, 2017). Overall, it seems that these trends form feedback loops which increase the challenges faced by dryland geo-ecosystems.

7 Rural and urban settlements, and other infrastructures

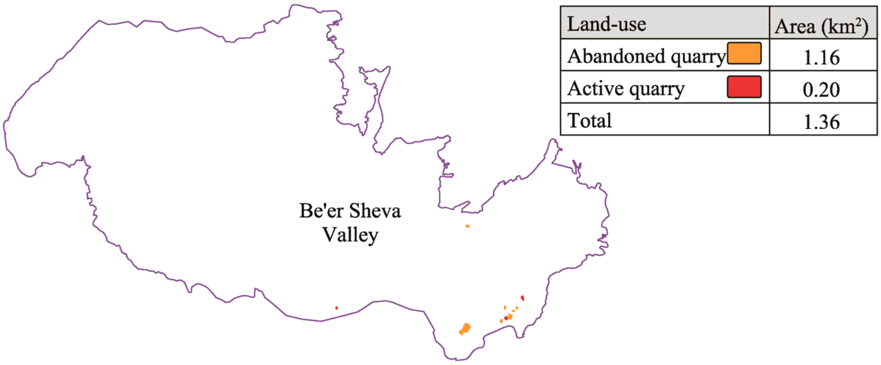
Over the recent decades, the human population of the northern Negev Desert has increased substantially, and the corresponding distribution of settlements, quarries, and nature reserves and parks across the loess plains is shown in Figure 3. In addition to natural (birth-driven) growth, this trend has also been affected by positive migration, which has recently replaced a long-term opposite trend of out-migration. The current demographic trend is expected to continue over the near- and mid-term future. Settlements cover 158.45 km^2 of the loess plains (Fig. 3a).

(a) Settlements



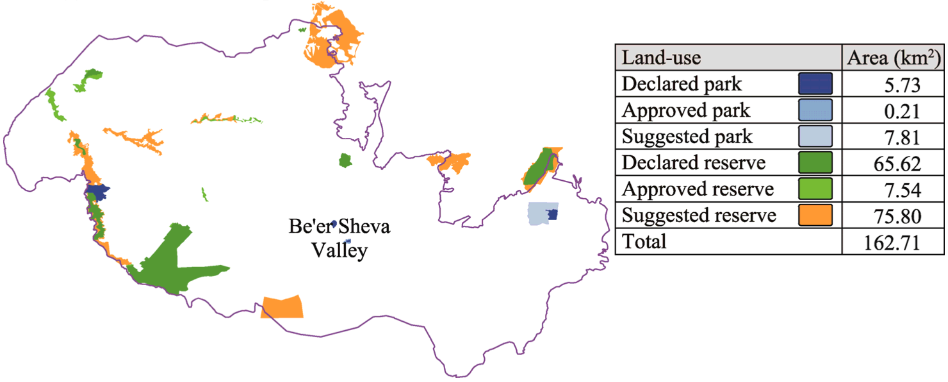
Land-use		Area (km^2)
Rural settlements	🟩	84.64
Urban	🟫	73.80
Total		158.45

(b) Quarries



Land-use		Area (km^2)
Abandoned quarry	🟧	1.16
Active quarry	🟥	0.20
Total		1.36

(c) Nature reserves and parks



Land-use		Area (km^2)
Declared park	🟦	5.73
Approved park	🟦	0.21
Suggested park	🟦	7.81
Declared reserve	🟩	65.62
Approved reserve	🟩	7.54
Suggested reserve	🟧	75.80
Total		162.71

Fig. 3 Distribution of settlements (a), quarries (b), and nature reserves and parks (c) across the loess plains. Figure 3a and b was produced based on open data obtained from https://deshe.org.il and Figure 3c was produced based on open data obtained from https://en.parks.org.il.

Compared to other regions of Israel, the northern Negev Desert has a substantially greater proportion of population living in rural settlements (defined as having up to 2000 inhabitants;

https://www.gov.il/en/departments/central_bureau_of_statistics/govil-landing-page; Weinreb, 2021). The region's Jewish population is 4.50×10^5, of whom 2.15×10^5 inhabit Be'er Sheva and 1.50×10^5 live in townships distributed across the eastern and western loess plains. The rest of the Jewish population inhabits *kibbutzim*, *moshavim*, and community settlements (0.85×10^5 people), found in the central and western loess plains (https://www.gov.il/en/departments/central_bureau_of_statistics/govil-landing-page).

The region's Bedouin population has also increased substantially over the recent decades, and currently numbers approximately 3.00×10^5 persons. Most of the Bedouin settlements are in the historical *Sayag* region, spanning about 1100.00 km^2 between Be'er Sheva to the west, Arad to the east, Yeruham/Dimona to the south, and the Yatir/Southern Hebron Mountain to the north. The Bedouin settlements include one city, six townships, two regional councils each with several recognized villages, and many spontaneous (unrecognized) villages (Weinreb, 2021). About one half of the Bedouin population inhabits the city/townships, while the other half lives in villages (https://abrahaminitiatives.org/bedouin-society-in-the-unrecognized-villages-in-the-negev-during-the-iron-swords-war/).

As elsewhere, settlements within the loess plains destroy expansive natural habitats, cause habitat fragmentation, and impact geo-ecosystems far beyond their territorial extent. For instance, light pollution adversely affects ecosystems at a distance from the light source (Ben-Moshe and Renan, 2022). Domestic waste imposes a major environmental challenge. Although most domestic waste is regularly transported to regulated landfills (Zisman et al., 2024), some waste is dumped near the settlements, resulting in on-site and off-site pollution of soil, water, and air resources (Eliyahu, 2019). Among the regulated landfills, the largest dumping site, Duda'im Landfill (31°19′44″N, 34°45′24″E), which also serves as a major landfill for other regions across Israel, attracts birds. Among them, predatory birds—specifically *Milvus migrans* Boddaert—overpopulate the site (https://www.dudaim.org.il/). Despite the subjective aesthetics that may be related to this effect, its ecological impact has not been studied. Yet, it has been reported that the expansion of this bird species worldwide is supported by landfills, and may adversely impact local ecosystems (De Giacomo and Guerrieri, 2008; Rabaca et al., 2021).

Population growth has necessitated the construction of substantial infrastructures throughout the region, including industrial zones, employment centers, and others, which have been established both near and far from settlements (Hatzbani and Atlan, 2020). Residues of construction materials, as well as industrial wastes that are sometimes hazardous, are transported to designated landfills in the Neot Hovav Industrial Zone (31°08′17″N, 34°47′56″E; also serving as an industrial landfill for other regions across Israel), where they are sorted, and then either recycled or buried (Neot Hovav, 2021). When not properly treated, these industrial zones and landfills emit gaseous and other pollutants, jeopardizing the quality of soil, water, and air resources (Cohen et al., 2012), adversely affecting ecological quality, and harming human health at a radius of several tens of kilometers (Givon, 2012). Landfills can also impose odor pollution, lowering the quality of life of local communities (Rosen-Zvi, 2007). Quarries and mines are also prevalent across the region, from phosphate fields in the eastern edge (Planning Administration, 2014) to gravel/pebble extraction from dry channel beds of many wadis across the northwestern Negev Desert, including Nahal Be'er Sheva, Nahal Besor, Nahal Ze'elim, and Nahal Revivim (Shikma-Besor Drainage Authority, 2018). Overall, quarries cover approximately 1.36 km^2 of the loess plains (Fig. 3b). In addition to these infrastructures, the expansion of railways, asphalt roads, paved roads, dirt roads, as well as other earthworks across the region, have further exacerbated the pressures imposed on the fragile environment by reducing ecological connectivity (Ben-Moshe and Renan, 2022). Although the effects of linear/elongated infrastructures have not been explicitly assessed for the northern Negev Desert, they likely impact hydrological connectivity and induce habitat fragmentation, hence affecting geo-ecosystem functions and services (Jones et al., 2000).

8 Passive and active restoration

Mismanagement, such as overgrazing and intensive tillage, has caused excessive land degradation across the loess plains. Some moderately-degraded lands or sites in relatively mesic regions may be restored using passive means, which are easier to perform and are less costly than active ones. The most common passive means is fencing of the target land, aimed at halting anthropogenic disturbances (Fig. 4a and b) (Zahawi et al., 2014). Over time, fencing is expected to promote vegetation establishment and improve soil quality, which foster each other through webs of feedback loops. For example, herbaceous vegetation and soil quality of a degraded rangeland in China were reported to gradually recover during 25 a of fencing (Guo et al., 2020). Longer-term fencing is expected to support recovery of more vegetative lifeforms, including sub-shrubs, shrubs (Zhang et al., 2012), and even trees, generating a diverse, multi-story plant community (Kobel et al., 2021). Simultaneously, pedogenesis enables the formation of soil horizons, and facilitates soil functions and services (Young et al., 2021).

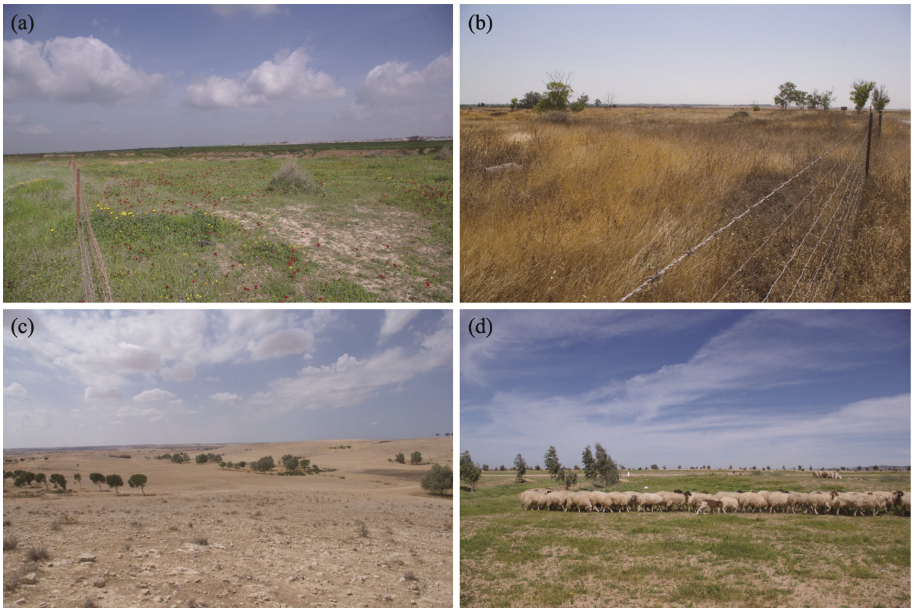


Fig. 4 Fencing as a passive restoration means of shrublands in the western Negev Desert (a and b), and afforestation systems as active restoration means relying on runoff harvesting systems such as contour bench terraces and limans in the northern Be'er Sheva Valley (c and d)

Nevertheless, while restoring rangelands, stocking rates should always be determined concordantly with the carrying capacity—the number of livestock that a unit of land can support within a certain period of time (Meshesha et al., 2019). Yet, in addition to forage productivity, quality, and palatability, additional aspects should be considered, including rainfall distribution, topographic characteristics, soil conditions, plant species composition, and the access to management tools and accessories (Eldridge and Squires, 2002). Regardless, a harvest efficiency of 12%–50% of the total forage biomass should be considered. Over time, harvest efficiencies increase in properly managed rangelands. As a general guideline, for every 1% increase in harvest efficiency, there is a 4% increase in rangeland's carrying capacity (Meehan et al., 2018).

Among the protected lands across the loess plains (Fig. 3c), the 40.00 km^2 Loess Park (31°14′25″N, 34°38′04″E) is an example of a successful passive restoration project. It exhibits substantial geodiversity, as well as a rich and diverse ecosystem. The park was declared a nature reserve to limit the expansion of croplands, settlements, and other engineered infrastructures in its surroundings, prevent livestock access, and preserve a wide range of historical/archaeological sites. A decade-old policy document recommended to further protect the loess plains by designating 10% of their total area as nature reserves, encouraging traditional land-uses, and halting future land-use change (Perelberg and Ron, 2014). However, not all passive restoration projects have been successful. For example, in the arid Sde Zin site (30°51′56″N, 34°49′49″E) that is approximately 35 km south of the loess plains, soil properties and herbaceous vegetation have slightly recovered following the fencing of an extremely degraded site over several decades, but shrubby vegetation has not reestablished (Stavi et al., 2023).

Active restoration is generally more expensive and complicated than passive restoration, therefore, it is generally applied to severely degraded lands or to sites in more xeric regions (Li et al., 2018). Among the active means, tillage is predominant, aimed at aerating the soil and reducing its compaction. Over time, this practice promotes soil genesis and vegetation development, which foster each other through a web of feedbacks. A previous study conducted in Sde Zin showed that following tillage of an extremely degraded land, soil quality was improved within a few years, and both herbaceous and woody vegetation recovered slightly (Stavi et al., 2018b). Inoculation by biocrusts is another active practice, as biocrusts stabilize the ground surface (Schultz et al., 2022) and increase resistance to erosion by water (Li et al., 2016) and wind (Fick et al., 2020). Additionally, biocrusts improve soil quality by sequestering organic C in the soil, and increasing the soil's nutrient content by fixating N (de Guevara and Maestre, 2022) and trapping atmospheric dust (Field et al., 2010). Yet, it has been reported that some compositions of biocrusts may decrease water infiltrability (Eldridge et al., 2000). Further, biocrusts may reduce the establishment of vascular plant species with certain seed size and geometry (Zhang et al., 2016). Another active means is the direct seeding of uni-species or multispecies herbaceous vegetation (Kirmer et al., 2012). Seeding was reported to effectively restore degraded lands by increasing plant coverage, richness, and diversity (Farrell et al., 2021), and controlling runoff and erosion processes (Kirmer et al., 2012).

Among active restoration means, afforestation (Fig. 4c and d) and reforestation are most prevalent worldwide, encompassing expansive dryland regions. In the northern Negev Desert, some afforestation projects have succeeded, however, several related challenges have been reported, such as pest infestation and degraded ecological health in monoculture forests (Golan et al., 2022), as well as allelopathy of the planted trees that may adversely affect the understory vegetation. Additionally, although dryland forests are commonly perceived to contribute substantially to C sequestration in soil and biomass (Neely et al., 2009; Amanuel et al., 2019; Zheng et al., 2023), the reduced albedo of the forests' surface questions their net impact on climate change (Rohatyn et al., 2023).

Wherever passive or active means are implemented, the geodiversity should be considered. Notably, high-geodiversity sites seem to better cope with long-term droughts and climate change compared to low-geodiversity sites. Consequently, restoration projects may be more successful in hilly sites with a thin and stony soil layer than in level sites with a thick and non-stony soil layer. Further, it seems that in active restoration projects, recovering or creating geodiversity may accelerate the restoration rate of the target geo-ecosystem. Such actions can be easily implemented by forming micro- or meso-topographic roughness. In stony sites, judicious use of stones may further increase surface roughness. Such means are expected to increase the on-site retention of runoff water, decrease water loss from the systems, improve pedogenesis, and accelerate vegetation establishment.

Proactive policy making and facilitative legislation are needed to conceptualize schemes for halting land degradation and accelerating the restoration of degraded lands across the region. Such schemes will provide stakeholders and land managers with the required means to successfully implement optimal plans of action. Further, combining conservation, regenerative, and climate-smart practices will improve the regions' capacities for climate change mitigation and adaptation (Fig. 5).

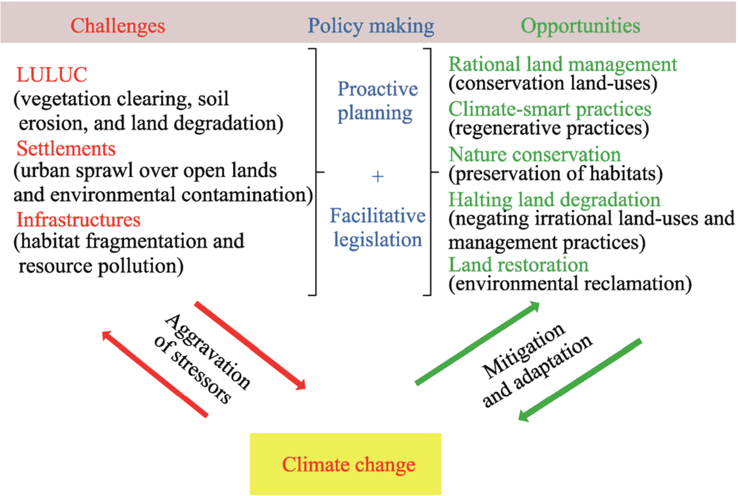


Fig. 5 A schematic diagram of the interrelations among challenges, policy making, and opportunities, and their interactions with climate change. LULUC, land-use and land-use change.

9 Conclusions

This study describes the challenges and opportunities faced by the loess plains of the northern Negev Desert in Israel, which encompasses unique habitats, diverse geo-ecosystems, and many plant species, several of which are endemic and/or endangered. Over time, and particularly in recent decades, anthropogenic stressors have increased tremendously, challenging the successful functioning of these plains. The major anthropogenic stressors are related to LULUC. Specifically, land-uses have changed from 'natural' lands to rangelands, rainfed or irrigated agricultural systems, and afforestation projects. In addition, land is used for the expansion of rural and urban settlements and construction of engineered infrastructures, such as roads, railways, mining areas, industrial zones, landfills, etc. The major factors jeopardizing the loess plains are as follows: vegetation clearing and soil erosion in rangelands; soil erosion, C pool depletion, and soil pollution in croplands; and reduced coverage and diversity of native plant communities, alongside plant species invasion, in afforestation lands. Simultaneously, settlements and infrastructures can cause environmental contamination and habitat fragmentation. Climate change, manifested by increasing temperatures and decreasing precipitations, exacerbates regional land degradation and desertification. Among the passive and active restoration projects implemented in the northern Negev Desert over recent decades, only some may be perceived as successful. The forecasted increase in climatic and (other) anthropogenic stressors in the near future require fundamental changes in policy making and environmental legislation, to ensure the effective conservation and restoration of the northern Negev Desert's loess plains.

Conflict of interests

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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Author contributions

Conceptualization: Ilan STAVI; Investigation: Ilan STAVI, Gal KAGAN, Sivan ISAACSON; Methodology: Ilan STAVI, Sivan ISAACSON; Software: Gal KAGAN, Sivan ISAACSON; Project administration: Ilan STAVI; Formal analysis: Gal KAGAN, Sivan ISAACSON; Writing - original draft preparation: Ilan STAVI, Gal KAGAN, Sivan ISAACSON; Writing - review and editing: Ilan STAVI, Gal KAGAN, Sivan ISAACSON; Funding acquisition: Ilan STAVI; Resources: Ilan STAVI; Supervision: Ilan STAVI. All authors approved the manuscript.

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