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The Middle East as a Natural Laboratory to Advance Our Understanding of Global Hyper-Arid Drylands

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Abstract

Contrary to the common perception of hyper-arid drylands as barren and lifeless, these regions are home to some of the planet's most unique biodiversity and support over 100 million people. Despite their ecological and human significance, hyper-arid drylands remain among the least studied biomes in the world. In this paper, we explore how improving our understanding of hyper-arid ecosystems in the Middle East can yield valuable insights applicable to other hyper-arid regions. We examine how ongoing greening initiatives in the Middle East offer a unique opportunity to deepen our knowledge of dryland ecology and advocate for the establishment of a comprehensive research program in the region. This program would focus on ecosystem functionality across spatial and temporal scales, setting the stage for a global monitoring network for hyper-arid drylands. Such efforts would inform conservation strategies and climate change mitigation, while also shedding light on the resilience and adaptability of hyper-arid ecosystems

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to environmental change. Ultimately, this monitoring would guide management practices to preserve biodiversity, enhance ecosystem services, and promote sustainable development in hyper-arid regions worldwide.

Keywords: drylands; hyper-arid; conservation; restoration; biodiversity.

Hyper-arid drylands, areas with an aridity index (precipitation/potential evapotranspiration) below 0.05, represent some of the most extreme environments on Earth. Despite the perception as being inhospitable to life, they host a diverse set of biota and ecosystems, including rangelands that provide grazing for nomadic tribes (Johnson, 1993), biocrusts that contribute to carbon sequestration (Kidron et al., 2015), or coastal mangroves and salt-marshes that support fisheries and modulate nutrient cycling (El-Regal and Ibrahim, 2014). Encompassing an area of around 10 million km^2, the extent of hyper-arid regions is expected to grow by the end of the century due to increasing aridity driven by climate change. Current projections estimate the expansion of hyper-arid land by 2050 to range from 6% under moderate scenarios to as much as 12% in the most pessimistic scenarios (Huang et al. 2016). While more than 100 million people currently live in hyper-arid drylands (MEA, 2005), population growth rates as high as 65% by 2100 have been projected for developing countries in these regions (Huang et al., 2016), placing further strain on these ecosystems.

Hyper-arid ecosystems remain poorly studied compared to other dryland and non-dryland ecosystems (Brito et al., 2014; Šmíd et al., 2021). Research on their biodiversity, structure, and function is limited, representing less than 3% of all dryland studies (Groner et al., 2023). These ecosystems are not only challenging to access (Ficetola et al., 2013), but also vastly under-protected, with just 6.7% of their total area designated for conservation (Lewin et al., 2024). The inaccessibility of hyper-arid areas, coupled with the misconception that they are barren and devoid of life, has resulted in their neglect in conservation efforts (Durant et al., 2012). Consequently, there is a widespread but incorrect belief that these environments are either ecologically insignificant or incapable of further degradation (Martínez-Valderrama et al., 2020). Contrary to this view, hyper-arid drylands are rich in biodiversity. For example, the Algerian Sahara alone is home to at least 1,200 plant species (Ozenda, 2004). Due to the unique adaptations of organisms in these extreme environments, hyper-arid ecosystems offer valuable insights into how dryland systems might respond to future climate change. They serve as natural laboratories for studying the impacts of, and adaptations to, climatic change that could affect other dryland regions (Groner et al., 2023; Grünzweig et al., 2022). Furthermore, as non-dryland areas face increasing water scarcity, mechanisms governing ecosystem functioning in drylands are expected to become relevant in these regions (Allan et al., 2020). Many of these changes are anticipated in densely populated regions, particularly in the subtropics and mid-latitudes, with significant implications for food production and societal well-being (Grünzweig et al., 2022). Beyond ecological insights, studying the adaptations of organisms in hyper-arid drylands holds great promise for biotechnological and biodiversity applications (Bull and Asenjo, 2013).

The Middle East accounts for over 30% of the world's hyper-arid drylands. This region hosts diverse biomes that have developed unique eco-evolutionary adaptations over thousands of years of biotic and abiotic interactions. They support more than 8,000 unique species of vascular plants (Hegazy and Doust, 2016) and encompass a diverse range of ecosystems present in other regions, albeit under more favorable conditions. These ecosystems span from mangroves along the coastal fringes of the Red Sea to grasslands and shrublands extending across Turkey and Iraq (**Box 1)**. Despite the geographic and historical interest the Middle East has generated, much of the research undertaken in this region has predominantly focused on the description of the flora in individual countries, such as Iran (e.g., Rechinger, 1963-2005), Israel and Palestine (e.g., Zohary, 1962; Danin, 2004), Lybia (e.g., Jafri and El-Gadi, 1977-1993), Oman (e.g., Ghazanfar, 1992, 1998), Saudi Arabia (e.g., Migahid, 1978; Mandaville, 2013), Turkey (e.g., Davis, 1984; Davis et al., 1988), or Yemen (e.g., Kilian et al., 2002; Brown and Mies, 2012). Other studies described the vegetation of the Middle East from geobotanical and phytogeographical perspectives (e.g., Zohary, 1971, 1973). Similarly, the fauna of the Middle East has drawn significant interest due to the extreme environmental conditions these species endure, with several biodiversity hotspots in the region. For example, the Arabian Peninsula hosts a high number of endemic vertebrate species, 21.6% of which are unique to this region (Mallon, 2011). Additionally, the Middle East serves as an essential stopover for migratory bird species along major migratory routes that connect Africa, Asia and Europe (Schekler et al., 2022). Countries like Israel have been extensively studied for their key role in bird migration routes for decades already (e.g., Leshem and Yom-Tov, 1996). However, except for Hegazy and Doust (2016), the life stories of many Middle Eastern species have not been comprehensively investigated and described while concurrently considering this region's geography, plant evolution and ecology. Moreover, these studies have yet to integrate the complex interactions between human societies and ecosystems, particularly in the face of the additional pressures imposed by climate change.

Here, we elaborate on how research on the biodiversity and ecology of Middle East hyper-arid drylands can advance our understanding of dryland ecosystems globally, while also contributing to the success of ongoing Saudi and Middle East Green Initiatives (https://www.greeninitiatives.gov.sa/). With an initial investment of more than USD 180 billion, these green initiatives aim to restore degraded marine and terrestrial environments, enhance biodiversity and mitigate the impacts of climate change throughout the Middle East. We argue that if these initiatives are successfully developed and implemented, they might serve as the foundation for further experimental and theoretical studies on the impacts of extreme climates on dryland ecosystems globally. Furthermore, the Saudi and Middle East Green Initiatives could establish the base for applied solutions aimed at preserving and/or rehabilitating the biodiversity and ecosystem services of global drylands, mitigating climate change and addressing land degradation and desertification.

Ongoing greening initiatives in the Middle East: An untapped potential to enhance our understanding of hyper-arid ecosystems

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To sustain its unique biodiversity into the future, it is crucial to promote the resilience and health of hyper-arid ecosystems, particularly given the compound pressures of anthropogenic influence and climate change. These are key objectives of the Saudi and Middle East Green Initiatives, which aim to protect up to 30% of Saudi Arabia's land and sea territories and plant up to 10 and 40 billion trees within the Kingdom and across the Middle East, respectively (https://www.greeninitiatives.gov.sa/about-sgi/ and https://www.greeninitiatives.gov.sa/about-mgi/, respectively). Other actions supported by these initiatives include the increase of renewable energy capacity – which has already risen by 300% in Saudi Arabia-, restoring degraded lands – 94,000 hectares have been rehabilitated across Saudi Arabia at the moment – and rewilding endangered species that play a key role in the ecological balance of these ecosystems. It is also expected that the Saudi Green Initiative will play a significant role in achieving the recent commitment of Saudi Arabia to reach net zero emissions by 2060, with the Middle East Green Initiative aiding broader regional objectives towards carbon neutrality. Moreover, the Saudi Green Initiative's ambition to protect at least 30% of Saudi Arabia's territories by 2030 is in harmony with the global "30x30" target adopted under the Kunming-Montreal Global Biodiversity Framework of the Convention on Biological Diversity (CBD, 2022). Although this is a challenging objective, 18.1% and 6.49% of Saudi Arabia's terrestrial and marine areas are already protected.

Both greening initiatives will protect some of the region's iconic terrestrial fauna, which are classified at varying levels of threat, ranging from vulnerable to critically endangered, according to the International Union for Conservation of Nature (IUCN) Red List of Threatened Species. Additionally, they will protect mangroves, coral reefs and salt marshes, which have co-evolved in this region to create some of the most resilient marine ecosystems globally (McCabe et al., 2023). Some of the Saudi Green Initiative activities include the creation of national reserves, such as the King Salman bin Abdulaziz Royal Reserve, located in the north of the Arabian Peninsula. Covering approximately 130,000 km^2, this reserve hosts vulnerable species of mammals (e.g., *Capra nubiana*, *Canis lupus arabs*) and birds (e.g., *Torgos tracheliotos*, *Falco cherrug*). Additionally, urban areas are targeted by these initiatives. Cities like Riyadh and Makkah in Saudi Arabia are seeing an increase in the number of trees planted and the creation of new green areas, enhancing human well-being and biodiversity (Gaston, 2010; Cox et al., 2017).

The Saudi and Middle East Green Initiatives should also learn from past actions and seek not only to ecologically transform broad landscapes but also to shape societies and economies. For example, the Great Green Wall for the Sahara and the Sahel Initiative (GGWSS), which emerged in 2007, involves over 20 countries bordering the Sahara to establish plantations on 100 million ha from Eritrea's Red Sea coast to Senegal's Atlantic coast (Sileshi et al., 2023). The GGWSS built upon earlier initiatives aimed at combating desertification in the Sahel region's countries (Mbow, 2017). One such initiative was Algeria's Green Dam Initiative, started in 1972, which aimed to establish a three million ha band of plantations to halt the northward advance of the Sahara Desert (Benhizia et al., 2021). Other projects, such as the Acacia operation project and the Support for the rehabilitation and extension of the Nouakchott green belt in Mauritania, engaged local communities and national authorities in restoring inland and coastland ecosystems (Berte, 2010). Projects in the Sahel region have shown that where policies and incentives are favorable, farmers actively promote the natural regeneration of trees, resulting in vast areas now being covered by trees (e.g., Haglund et al., 2011). A participatory approach involves extensive community engagement and enhances accountability and stewardship in land-restoration efforts. Initially, a

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centralized approach, heavily reliant on forest department control and substantial investment in equipment, marginalized local communities. Recognizing community ownership has enabled Sahelian countries to mitigate conflicts between development and environmental goals (Kumar, 2003). However, land privatization in the Sahel often fails due to diverse landscape uses and stakeholder needs (Schoneveld, 2017). These failures underscore the necessity for stakeholder-supported, site-specific solutions that enable ongoing improvement across countries and implementation sites. Learning from experiences in the Sahel region, local actions that can be scaled up with positive results include the zoning of grazing areas, ensuring water availability for livestock, and promoting fodder trees (Mbow, 2017).

In Asia, the Great Green Wall of China (GGWC), initiated by the Chinese government in 1978, aims to combat desertification and reduce the eolian transport of dust from the Gobi Desert (Parungo et al., 1994). Scheduled for completion in 2070 (Lu et al., 2018), this project builds on China's experience with shelterbelt programs (Qi and Dauvergne, 2022). While the GGWC has yielded benefits, such as reduced dust movement and increased vegetation, during its first stages, many of the dryland areas targeted for afforestation were found to be better suited for grasslands and steppes than woodlands or forests (Cao et al., 2010; Mátyás et al., 2013), often leading to significant water pressures on water resources (Li et al., 2021a). Not only tree survival rates were low but also irrigation was necessary in drier areas within many of these projects (e.g., Wang et al., 2020). Nevertheless, subsequent research has demonstrated the benefits of shelterbelts in drylands for reducing net erosion (Su et al., 2021) and improving crop productivity (Zheng et al., 2016). Additionally, studies on biocrusts in China's drylands have shown that breeding them can effectively control land degradation (Li et al., 2021b) by reducing dust emissions and increasing soil nutrient content (Li et al., 2010; He et al., 2019). Because of these experiences, new strategies in China now focus on science-based activities, encouraging natural regeneration, creating multi-species plantations, matching species to local conditions and emphasizing water conservation (Turner et al., 2023).

Over the past four decades, Australia has also made significant advancements in restoring its drylands through sustained efforts and community involvement (Campbell et al., 2017). Initiatives in Australia learned from small-scale efforts and led to a shift in policies towards large-scale activities, biodiversity conservation, water quality improvement and greenhouse gas mitigation. Successful restoration programs underscored community capacity and commitment, yet it was also recognized that community efforts alone were insufficient for sustainable resource management on a landscape or continental scale without technically and economically viable land use and farming systems. These lessons are particularly important in drylands, where synergistic interactions such as grazing intensification, drought, climate change, reduced fire frequency, and changes in atmospheric chemistry or small animal populations can collectively overwhelm the effects of individual factors (Fu et al., 2021a).

Restoration in the Middle East cannot be based only on planting trees in the desert

Ambitious tree-planting objectives are not a new concept, even in drylands (Bond et al., 2019). Unfortunately, many previous dryland afforestation efforts have often delivered tree monocultures,

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which risks reducing sustainable development by negatively affecting ecosystem functioning (Yao et al., 2021). Apart from avoiding planting regimes that are incompatible with the landscape, the inherent constraints of water availability in drylands, and the increased pressures that large-scale tree planting places on these, are critical considerations when designing greening and restoration efforts (Schwärzel et al., 2020). Although intrinsically appealing from a policy perspective (i.e., planting trees is a socially recognizable and acceptable climate action), excessive focus on afforestation using trees can miss opportunities for broader and longer-term benefits. For instance, mono-specific tree plantations may achieve a narrow accounting-based objective (in terms of trees planted or carbon captured) but they can reduce ecosystem diversity (e.g., Maestre and Cortina, 2004), jeopardize water resources for humans and ecosystems (e.g., Feng et al., 2016), and amplify the risk of future carbon loss following any ecosystem disturbance (e.g., forest fires and pests; Anderegg et al., 2020). In other parts of the world, regions deemed degraded have been mistakenly considered as potential areas for afforestation, simply by failing to carefully assess their suitability for tree planting (e.g., soil health, environmental gradients). Such areas have included grasslands and shrublands (Veldman et al. 2019), which represent two of the more common environments found in the Middle East (Box 1; Hegazy and Houst, 2016).

Recognizing the limitations and unintended consequences of prior afforestation strategies underscores the importance of adopting a more nuanced approach to ecosystem restoration, particularly in hyper-arid regions. Increased biodiversity is considered an indicator of healthier and more resilient ecosystems, allowing faster recovery from disturbance and providing ecosystem services that contribute to more sustainable and stable human development (Jactel et al., 2017). Thus, restoration and conservation efforts should act in concert to increase biodiversity, thereby bolstering the resilience of all naturally occurring ecosystems. This holistic view is crucial if the goal is to restore the multifaceted ecosystems of hyper-arid lands, considering the variety of services they provide (Box 1). For example, biocrusts are key players in dryland development and function that increase soil carbon and nutrient contents, impact multiple components of the hydrological cycle, and reduce soil erosion and dust emissions (Eldridge et al., 2020; Rodríguez-Caballero et al., 2022), benefitting both the environment and human societies. Therefore, the development of a biocrust research program is urgently needed to understand their ecology, distribution and potential to restore degraded habitats and mitigate climate change in the Middle East.

Restoration and greening initiatives in the Middle East should focus not only on what is visible above ground but also on soils. Over 32% of the world's soil organic pool is stored in drylands worldwide (Plaza et al., 2018a), with significant loss of carbon occurring in major cropland and grazing areas (Sanderman et al., 2017). However, although soils' potential to mitigate climate change has been long recognized (Bossio et al., 2020), their role in dryland restoration and mitigation efforts remains underexplored. Soil organic carbon can act as a stable carbon sink, showing resilience to land-use changes and disturbances, unlike above-ground biomass. Carbon-rich soils also enhance water and nutrient retention, enhancing ecosystem resilience to disturbances like droughts (e.g., Izumi and Wagai, 2019). However, regional evaluations of soil organic carbon in drylands remain limited, with existing studies often producing inconsistent results (Fu et al., 2021b). Furthermore, understanding the impact of land-use changes on regional soil carbon is hindered by insufficient data quality, poor representativeness, and a lack of historical land-use information (Hendriks et al., 2016). Comprehensive assessment of soil carbon stocks requires

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robust sampling methods that can scale site-specific data to broader regional levels (Ciais et al., 2011), an ongoing challenge in terrestrial carbon studies (Zhang and Hartemink, 2017). As such, a regional dataset combining soil organic carbon, land-use, and soil properties for the Middle East would enhance our understanding of how climate influences physical processes in global drylands. For instance, increasing aridity is known to reduce soil carbon and nitrogen levels (Delgado-Baquerizo et al., 2013) and disrupt nutrient balance in dryland soils (Maestre et al., 2016). Carbon accumulation in soils is influenced by factors such as parent material, topography, microclimatic conditions, and species diversity (Ramesh et al., 2019), while human activities can accelerate carbon emissions (Schlesinger, 2000; Lal, 2004a). Although improved management strategies (e.g., grazing regimes, organic amendments, cover crops, crop rotation and conservation tillage) can enhance carbon stocks in dryland soils (Plaza et al., 2018b; Lal, 2004b; Lal, 2018), they can be less effective in these environments due to their coarser texture and lower clay content, which protects organic matter from decomposition (Six et al., 2002; Lehmann and Kleber, 2015). It is, therefore, crucial to evaluate the interactions between biotic, abiotic and human factors to understand soil C dynamics in the Middle East.

Concluding remarks

Hyper-arid lands have been largely missing from existing large-scale global dryland field surveys (Maestre et al., 2012, 2022b). The Saudi and Middle East Green Initiatives provide a unique opportunity to gain insights into the processes that govern the structure, functioning, and responses to climate change of hyper-arid drylands. Knowledge gaps that need to be addressed include understanding: i) the drivers for the unexpected high functional diversity in dryland plants (Gross et al., 2024); ii) how plants will adapt to water scarcity and respond to increased inter-annual precipitation variability (Garcia-Pichel and Sala, 2022); iii) developing a region-wide understanding of the distribution, characteristics, and functioning of biocrusts (e.g., Abed et al., 2019), and iv) the mechanisms, both physiological and genetic, behind the ability of soil microorganisms to endure extreme conditions (Makhalanyane et al., 2015). Further, many remote sensing-derived products ignore hyper-arid drylands based on the assumption that vegetation is largely absent. As a result, hyper-arid drylands are often excluded from remote sensing products typically used in global studies and vegetation estimates (e.g., Harris et al., 2021; Sabatini et al., 2022). This is problematic, as vegetation (and trees in particular) is more abundant in hyper-arid areas than initially thought (Brandt et al., 2020; Reiner et al., 2023). More generally, international networks evaluating ecosystem carbon, water, and energy fluxes, such as FLUXNET (Baldocchi et al., 2001), lack sites in hyper-arid environments, despite these representing around 8% of global land surface (Prăvălie et al., 2019). Developing an augmented flux network that includes sites in the Middle East would provide invaluable information on hyper-arid drylands, and contribute to fill existing gaps in flux databases that preclude obtaining more precise carbon cycling and climate change impact estimates.

Many of the actions discussed here will occur in complex and unpredictable contexts, where human realities should be considered alongside ecological and biophysical factors. Drylands exhibit sensitivity to changes in structure-function relationships due to extreme climate conditions (Reynolds et al., 2007; D'Odorico and Bhattachan, 2012), and human interventions can alter the

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resilience and stability of these systems (Robinson et al., 2015). Interactions between natural and human-induced processes affect dryland dynamics at specific scales (Fu et al., 2021a), varying by social, cultural, and economic context (Stringer et al., 2017). Therefore, understanding the complex and adaptive nature of drylands in the Middle East should involve dynamic interactions between its ecosystems and human societies (Folke et al., 2016; Schütler et al., 2019), requiring interdisciplinary efforts (Bautista et al., 2017; Schütler et al., 2019).

Research in the Middle East should focus on the interplay between ecosystem services and human well-being to optimize services that enhance drylands' health and human well-being in the long term (Fu et al., 2021b). Identifying local limiting factors and their impacts can improve knowledge of ecosystem functioning and livelihoods through sustainable development (Turner et al., 2003; Reed et al., 2015). An interdisciplinary approach, which evaluates ecological and social perspectives together, will allow for assessing ecological dynamics and their driving forces in the Middle East. It will not only enable an understanding of the macroscopic differences among various dryland systems in this region but also help identify management or policy responses likely to deliver successful outcomes in different types of drylands (Fu et al., 2021b).

Developing a comprehensive research program on ecosystem structure and functioning across multiple spatio-temporal scales in the Middle East is a critical step to provide the scientific underpinning needed for the success of ongoing green initiatives and climate change and desertification mitigation actions in this region. The creation of a Middle East collaborative network of researchers, practitioners, and decision-makers, and the set-up of standardized regional surveys using standardized protocols following models successfully implemented in other large-scale and global surveys (e.g., Maestre & Eisenhauer 2019; Maestre et al., 2022a), would be a fundamental step forward towards achieving this aim. Doing so would not only be key to creating the basis for long-term monitoring of ecosystem changes in the region, but would provide us with invaluable insights to advance our understanding of hyper-arid drylands and to better comprehend and react to the increasingly drier conditions being experienced and forecasted across the globe.

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Author Contribution Statement

J. B.-S. conceived the idea and wrote the initial draft; all authors contributed to the review and the final version of the manuscript.

Conflict of Interest Statement

The authors declare that they have no conflict of interest.

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Box 1. Hyper-arid drylands in the Middle East are much more than barren landscapes.

The Middle East is home to diverse ecosystems that, while also found in other regions under more favorable conditions, can thrive in some of the driest environments on Earth. Gaining a deeper understanding of these ecosystems offers valuable insights into their functioning, restoration potential, and relevance for addressing climate change, land degradation, and desertification. For instance, mangroves (1) along the coasts of the Red Sea and Arabian Sea (Almahasheer et al., 2018; Blanco-Sacristán et al., 2022) are a key vegetation type in the Middle East. These ecosystems provide nursery grounds for marine life, support local communities through commercial species, and protect coastlines from erosion. However, mangroves in this region endure extreme saline stress due to limited freshwater inputs and increasing groundwater extraction, on which they heavily rely (Adame et al., 2021). Additionally, these mangroves face significant human pressures (Almahasheer et al., 2016). Understanding how mangroves survive in such arid conditions offers a unique opportunity to predict how global mangrove ecosystems might respond to climate change, including the effects of human activities, sea-level rise, and microclimatic shifts (Osland et al., 2016). Similarly, the grasslands (2) of the Middle East, such as those in Iran's Taftan mountains (Burrascano et al., 2018) and the southwestern Arabian Peninsula (Ghazanfar and Fisher, 1998), provide a valuable opportunity to study the interactions between abiotic and biotic factors across altitudinal and latitudinal gradients. As global aridity increases, understanding the dynamics of these grasslands—ranging from Mediterranean grasslands to semi-arid steppes—can offer crucial insights for improving grassland health in other dryland regions. This is particularly important given the extreme climatic conditions in which these grasslands exist, which mirror those in many other arid and semi-arid ecosystems globally, such as the grasslands in the Namib Desert (Evans et al., 2020; Logan et al., 2021) and Australia (Keast, 2013). By studying how these Middle Eastern grasslands thrive, researchers can gain a deeper understanding of the resilience and adaptive strategies of grassland ecosystems, crucial for managing the effects of climate change on grasslands worldwide. Shrublands (3), which dominate much of the Middle East—such as the eastern Arabian Peninsula, parts of Jordan (e.g., Jebel Ajloun), and northern Israel (Upper Galilee)—also play a critical ecological role. They provide habitats for insects and small rodents and host biocrusts—communities of photo- and heterotrophic organisms living on the soil surface in large, unvegetated drylands. Biocrusts are essential for maintaining dryland ecosystem health by influencing soil respiration, nutrient cycling, and runoff dynamics. While biocrusts have been extensively studied in regions like the Negev Desert and the Arava Valley in Israel (e.g., Galun and Garty, 2003; Kidron and Tal, 2012), research across other Middle Eastern countries is limited. Studies from countries like Iran (Bashtian et al., 2019), Iraq (Hamdi et al., 1978), Jordan (El-Oqlah et al., 1986), Oman (Abed et al., 2013), and Saudi Arabia (Alotaibi et al., 2020) suggest that biocrust composition is relatively uniform across the region (Galun and Garty, 2003), but more research is needed to fully understand their distribution and composition in the Middle East. With its long history of land use and anthropogenic impacts under climate change (Kaniewski et al., 2012), the Middle East offers valuable insights into how human activities shape biocrust communities under extreme environmental conditions. Studying the interactions between biocrusts and human-induced changes—such as grazing, agriculture, and urbanization—can inform strategies for managing and mitigating these impacts, both regionally and globally. Leveraging remote sensing technologies (e.g., satellites, drones, and eddy-covariance towers) alongside in-situ data collection could enhance ecosystem surveys, providing timely insights into their functioning. This data could also support the establishment of new monitoring networks, such as eddy

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covariance flux networks, which remain underrepresented in hyper-arid drylands worldwide (Smith et al., 2019).

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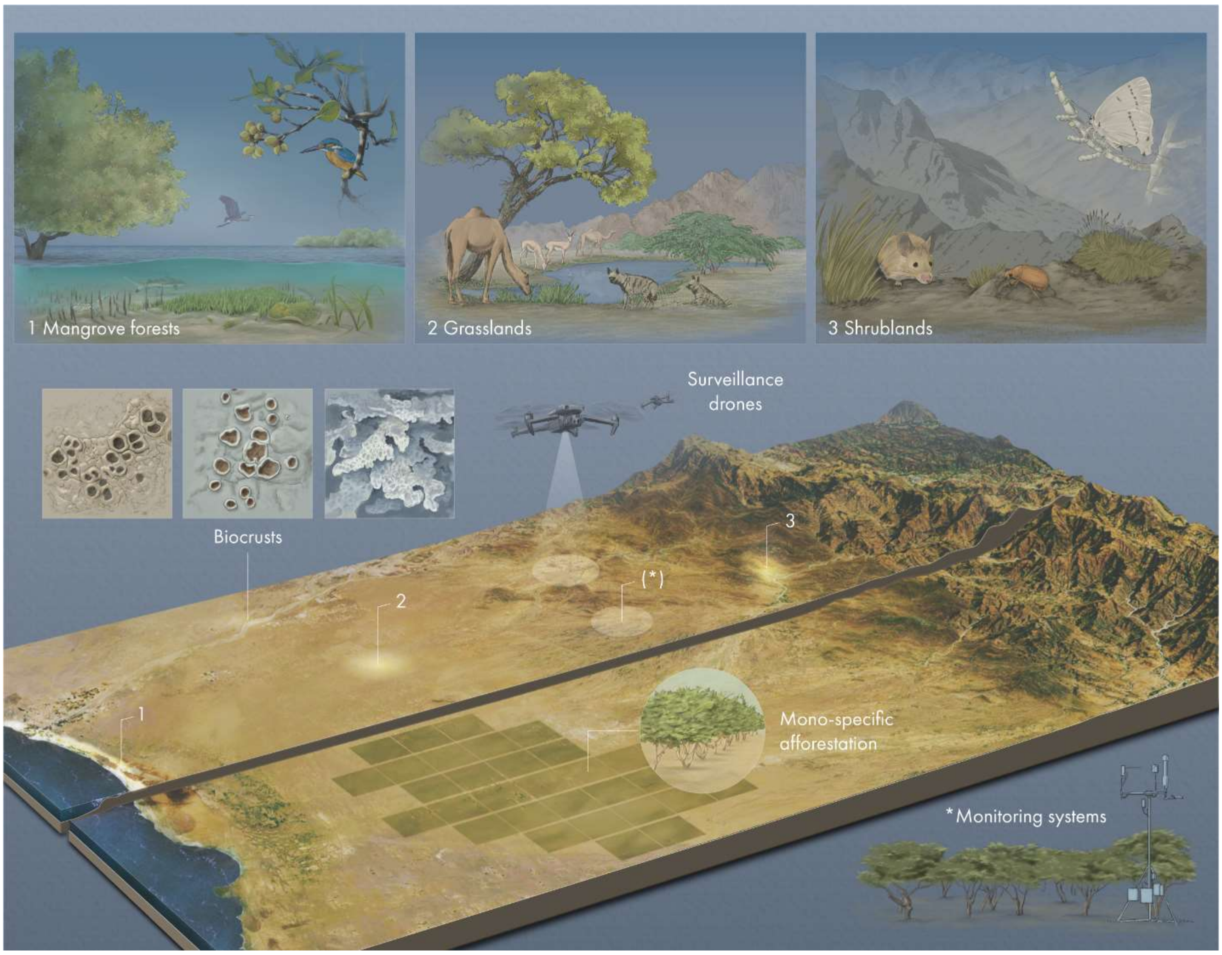

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