

Aligning Mine-Site Landscape Rehabilitation with National Afforestation Targets in Saudi Arabia: An Evidence Synthesis and Sustainable Landscape Management Framework for Arid Regions

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Received: 12 Jun. 2026, Revised: 21 Aug. 2026, Accepted: 25 Sep. 2026

Published online: 1 Nov. 2026

Abstract: Mine-site rehabilitation is rarely quantified as a contributor to national afforestation and landrestoration targets, particularly in hyper-arid regions. This study develops an evidence-synthesis and quantitative sustainable landscape-management framework for Saudi Arabia. We integrate 37 verified peer-reviewed studies, official forest and greening statistics, mining-sector data, deterministic scenario analysis, and a multi-criteria certification model. Official reporting records more than 159 million trees planted and 1.0 million ha rehabilitated by early 2026, while current national pathways distinguish a 2030 operational phase (215 million trees and 2.5 million ha), a broader 2030 policy reference of more than 600 million trees, and the long-term target of 10 billion trees associated with approximately 40 million ha of rehabilitation. For mine land, three base scenarios yield 28–224 million gross planted stems and 70,000–280,000 rehabilitated ha by 2040. A 3×3 sensitivity matrix demonstrates linear dependence on annual rehabilitated area and planting density. We further formulate a Sustainable Landscape Management Index (SLMI) that combines normalized soil, vegetation, fauna, landscapefunction, socio-economic, and governance indicators with certification and additionality gates. The framework converts mine-closure obligations into auditable landscape outcomes without treating illustrative planting scenarios as forecasts.

Keywords: Arid-region restoration; mine-site rehabilitation; sustainable landscape management; applied mathematical model; multi-criteria decision support; Saudi Green Initiative; land degradation neutrality.

1 Introduction

Land degradation is one of the most important environmental challenges of the 21st century, threatening up to 40% of the terrestrial surface of the Earth and more than 3 billion people [1, 2]. The response from the international community has been unprecedented with the Bonn Challenge to restore 350 million hectares of degraded land by 2030 [3] and the United Nations Decade on Ecosystem Restoration (2021-2030) [4]. Two billion hectares, identified to offer opportunities for forest landscape restoration (FLR) have shaped national commitments in the dry tropics and subtropics [5, 6]. In

arid and hyper-arid countries, however, the conversion of these global aspirations to national programmes and plans is further complicated by current chronic water shortage, low natural tree cover and by land uses that erode green infrastructure, in particular, mining. A lot has happened in the world of restoration science since the conceptual consolidation of restoration. The field's basic conceptual framework was developed by Hobbs and Norton [7] and associated with chose of restoration intervention that is suitable with respect to diagnosed degradation threshold. Subsequent syntheses outlined the evolution of restoration from a small-scale niche project to a global industry [8], restoration's potential for delivering

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ecosystem services [9] and the conflicts and synergies between restoration of degraded lands and delivery of ecosystem services [10].

More recent contributions have served to clarify good practice - Lewis et al. [11] recommended more natural forest recovery than large-scale planting, where feasible, and Brancalion and Holl [12] and Di Sacco et al. [13] offered operational guidance on avoiding spending money on poor quality planting and the use of site-appropriate and native species. A recurring theme in this literature is the requirement for standardized indicators to measure success [14] and that there are still only selected indicators and ecosystems that are evaluated and published [15]. Mining is in a unique place in this discussion, since it is both a source of degradation and a possible source of restoration opportunity; it is an opportunity that is concentrated in terms of area, and has abundant resources. The global scale of extractive activity is not only beyond the boundaries of the leases, but the impacts of the leases are too: During the 11 years between 2005 and 2015, the mining activity in the Brazilian Amazon caused 11,670 km² of deforestation, which is 9% of the total deforestation in the Amazon during these 11 years, with effects up to 70 km away from the perimeter of the leases [16].

The highly modified substrates and the absence of soil structure and the toxicity of metals make it difficult to rehabilitate mined lands, and the fields of purpose-built approaches, such as phytostabilisation of tailings in arid environments [17] and rhizosphere engineering for sustainable tailings revegetation [18] and soil-quality indexing to quantify the trajectory of reclamation over decades [19] are limited. For instance, chronosequence evidence indicates that reclaimed mine soils can recover the carbon, nitrogen and phosphorus stocks within 10 years after forestation, particularly when using amendments such as biochar. Complementary insights are on the balance between technical reclamation and spontaneous succession [20], the integration of degradation and restoration models [21] and the use of fauna as indicators of recovery [22]. Overall, this literature substantiates the ability of mined-land rehabilitation to be ecologically successful, but to date, it is rare to see mined-land rehabilitation represented at the national scale [23].

Saudi Arabia is an illustrative context in which to explore this integration. The officially recorded forest area is low (9,770 km²) at 0.45% of the country's land area, which has remained the same since 1990 in international statistics [24] due to the naturally low level of forest cover in the Arabian Peninsula and to the limitations of the national forest accounting systems. But there is value in natural woody systems: juniper woodlands in the southwestern highlands are vulnerable to climate change-induced dieback [25], decades of open grazing have changed rangeland vegetation [26, 27] and land degradation is affecting the dynamics of the dust cycle and its impacts on human health and infrastructure

across the region [28]. The Saudi Green Initiative (SGI) has defined some of the most ambitious restoration targets in the world to plant 10 billion trees; to rehabilitate some 40 million hectares of degraded land; to protect 30% of terrestrial and marine areas; and to reduce CO₂e emissions by 278 million tonnes per year by 2030 [29]. Ministers' communiqué on the Middle East Green Initiative, which aims at planting 50 billion trees in the region, is continued to lead regional efforts [30]. Progress has been quick in early implementation, with over 159 million trees planted and the first one million hectares of degraded land rehabilitation, according to official sources by early 2026. While recent reporting for the National Greening Program is for the first phase out to 2030, with a commitment for 215 million trees and 2.5 million hectares of greenery, previous policy statements from the SGI are a more general 2030, with over 600 million trees. It is here these figures co-exist and are not silently melded together [31, 32].

Independent studies have begun to raise the question of whether these schemes fit into the sustainable development goals (SDG) [33]. There is much to be learnt from dryland restoration practice in the Arabian environment. In the Iberian semiarid southeast, there are some key lessons to keep in mind: Vegetation establishment in water-limited systems is more likely to be successful when site preparation, species selection and long-term protection are considered as a system; and when expectations are tempered and it is understood that success may take many decades [34]. In the case of gypsum-quarry system, which is a direct application to mining, experimental results have demonstrated that conditioning of substrates and retention of material in the site may be decisive in plantings in such dry and rocky sites [35]. The importance of the facilitative effect of presence of early established shrubs on later species, called nurse-plant facilitation, is now no longer a curiosity of the ecology, but a design principle in degraded dry environments [36]. The stakes are multiplied by the regional degradation context: Land degradation now is known to contribute to anthropogenic sand and dust storm generation with transboundary impacts [28] and therefore surface stabilization is one of the more direct policy returns on restoration investments in the Arabian Peninsula. At the same time, Saudi Arabia is going through one of the world's most ambitious mining sector expansion initiatives. The third pillar of the national economy according to Vision 2030 is mining, and it estimates the Kingdom's mineral wealth at around SAR 9.4 trillion [37]. The regulatory framework was modernized by enacting the Mining Investment Law through the Royal Decree No. M/140/2020 that took effect on 1 January 2021 and that encompasses modern provisions for licensing and environmental and closure obligations [38]. The sector is controlled by the Saudi Arabian Mining Company (Ma'aden), a state owned company that owns the largest assets in the sector, such as five gold operations, two bauxite mines and the phosphate

mining asset Hazm Al-Jalamid [39]. The company's total production in 2023 was 407 thousand ounces of gold, 895 thousand tonnes of primary aluminium and a record 9.099 million tonnes of phosphate products [40]. Historical legacy related issues with associated groundwater environmental impacts have been reported in the vicinity of Mahd Adh Dhahab gold mine, which is an example of the environmental burden of mining in the Kingdom [41]. With each expansion of the mines comes a legacy of unrehabilitated pit, waste rock dumps, tailings storage facilities, and industrial footprints that will ultimately require management. While the scope of the two programmes are vast, no relation exists between the two policy streams, whether institutionally or analytically, except the national afforestation and the mine rehabilitation. There are three gaps that can be addressed by this research. First, there is no published evidence on the ability to account for rehabilitating mine land in Saudi Arabia towards the SGI's targets for trees planted and rehabilitating land using an auditable additionality rule. Secondly, most of the evidence and information about mine rehabilitation in arid zones comes from studies elsewhere and benchmarks on survival, soil development and costs have not been systematically assessed for applicability to Arabian conditions [15, 34]. Third, the governance frameworks set up under the Mining Investment Law have not been investigated as a way of delivering verified restoration results that can be recognized by national accounting systems [4, 38]. This study seeks to address these gaps, with three objectives: (i) to distill and synthesize verified evidence of global and regional ecological outcomes of mine-land rehabilitation, with a special focus on arid systems, (ii) to characterize the current scale, growth and spatial concentration of the Saudi mining sector and associated degraded-land portfolio using verified official data, and (iii) to develop a framework for sustainable landscape-management including a conceptual pathway, a matrix for screening native species, scenario-based contribution estimates, and a key-performance-indicator (KPI) system for monitoring, through which certified mine rehabilitation can contribute to the national afforestation targets. The remainder of the paper details the materials and methods Section 2, the results Section 3, matters of feasibility, governance and policy Section 4 and the conclusions Section 5.

2 Materials and methods

2.1 Overall study design

This research is based on three pillars: systematic evidence synthesis, analysis of the verified secondary evidence data and development of an applied sustainable landscape-management framework. It attempts to tackle a restoration assessment challenge in data-poor areas – how

to reconcile the peer-reviewed evidence (which is developed elsewhere and in different contexts from the actual assessment) with the national statistics and corporate disclosures that are used to inform policy [8, 15]. Pillar One (published-evidence synthesis) gathered and verified peer-reviewed evidence on the outcomes of restoration and mine rehabilitation in accordance with the published-evidence synthesis screening process flow and inclusion criteria. Pillar II (secondary-data analysis) yielded official statistics on forest cover, green-initiative goals and achievements as well as the actions and production of the mining sector, all of which could be traced back to a primary institutional source. Pillar III (framework development) fed the results of Pillars I and II into a conceptual rehabilitation-to-afforestation pathway, a screening matrix for native species and scenario based contribution estimates as well as a monitoring KPI framework. The three pillars were performed in order and repeated if verification process didn't provide the required data but there were no primary field data collected, so this study was a documental and analytical synthesis.

2.2 Secondary data sources, extraction, and validation

Secondary data was obtained from institutional sources that were authoritative and reproducible from July to September 2026. The data for forest-cover was taken from the World Bank open-source API for the indicator AG.LND.FRST.ZS (forest area, % of land area), AG.LND.FRST.K2 (forest area, sq. km), and AG.LND.TOTL.K2 (land area, sq. km) for Saudi Arabia, for the time period 1990–2022; this data is collected by the World Bank from FAO reporting and is publicly accessible using the API endpoint. The green-initiative data come from the following official Saudi data: 10 billion trees, 40 million hectares rehabilitation commitment, 30% terrestrial and marine protection by 2030, 278 million tonnes CO₂e per annum emission reduction by 2030, and 2030 SGI policy reference (in excess of 600 million trees), as well as the National Greening Program first-phase pathway (215 million trees, 2.5 million hectares by 2030; [32]) and a recent release by the Ministry of Environment, Water and Agriculture (progress as of March 2026; more than 159 million trees planted, one million hectares of degraded land restored, and trajectory of 18,000 hectares by 2021, 250,000 hectares by 2024, and 2.5 million hectares planned by 2030).

Data for the mining sector were derived from Ma'aden's 2023 and 2024 Board of Directors' reports, which also provide historical series reported in the documents, and include annual productions of gold (in ounces), primary aluminum (tonnes), and phosphate fertilizer (tonnes DAP/MAP) as well as operational

descriptions at the site level, which were reported for 2024 only. The regulatory framework is taken from the official English version of the Mining Investment Law (Royal Decree No. M/140). Key figures were cross-validated with at least one independent secondary source, as far as possible, (for example, the gold output was reported to be 407 thousand ounces in 2023 and confirmed by a trade-press report in the same year); figures which could not be cross-validated with at least one independent secondary source were excluded or flagged as unverified. Unless otherwise stated in the source documents, all currency values are expressed in Saudi riyals (SAR) and at nominal values, without deflation.

2.3 Mathematical formulation, scenario analysis, and decision-support model

A total of five analytical procedures were used. The series pertaining to the mining sector were first of the descriptive growth accounting type. Year-over-year changes were based on adjacent observations of the variables in year t ; compound annual growth was based on the first and last observations in the seven years series. Second, evidence-synthesis matrix coded ecosystem type, intervention and outcome direction; quantitative values were only extracted when they were explicitly reported in verified sources and no imputation. Third, the planting potential for mine-land was modeled transparently with a deterministic approach. Gross planted stems are the number of annual gross planted area $\times$ establishment density for scenario s over horizon H . If the area and density values are constant, the model can be simplified to the product of horizon, area and density. Contributions are reported as percentages to explicit targets for trees and land dates.

$$YoY(t) = 100 \times \frac{V(t) - V(t-1)}{V(t-1)} \quad (1)$$

$$CAGR = \left[\frac{V(2024)}{V(2018)} \right]^{1/6} - 1 \quad (2)$$

$$T(s, H) = \sum_t A(s, t) D(s, t);$$

for constant A, D : $T = H \times A \times D$ (3)

$$C(s) = \frac{100T(s)}{T_{ref}}; \quad L(s) = \frac{100\sum_t A(s, t)}{A_{ref}} \quad (4)$$

The base scenarios use $H = 14$ years (2027–2040): conservative $A = 5,000$ ha yr⁻¹ and $D = 400$ stems ha⁻¹; moderate $A = 10,000$ and $D = 600$; ambitious $A = 20,000$ and $D = 800$. To expose parameter sensitivity rather than hide it inside three paired assumptions, a full 3×3 factorial matrix was also computed from

$A \in \{5,000, 10,000, 20,000\}$ and $D \in \{400, 600, 800\}$. Because the model is multiplicative, the local elasticities with respect to annual area and planting density are both equal to 1: a 1% change in either parameter produces a 1% change in gross planting potential, holding the other parameter constant. These quantities describe planting capacity, not survival-adjusted or credited outcomes.

$$\text{Elasticity}(A) = 1; \quad \text{Elasticity}(D) = 1 \quad (5)$$

Fourth, the seven monitoring domains in Table 7 were formalized as a multi-criteria Sustainable Landscape Management Index (SLMI). For site i and indicator k , observed values are normalized to a 0–1 scale using benefit-oriented or adverse-oriented min–max rules. The composite SLMI is the weighted sum of normalized indicators, with non-negative weights summing to 1. Equal weights are the transparent default when stakeholder-derived weights are unavailable; alternative weights can be declared and sensitivity-tested. Certification requires both a composite threshold τ and a minimum-domain threshold $\tau_{\min}$ to prevent a high score in one domain from compensating for ecological failure in another.

$$z_{ik} = \frac{x - L}{U - L} \text{ (benefit); } z_{ik} = \frac{U - x}{U - L} \text{ (adverse)} \quad (6)$$

$$SLMI_i = \sum_k w_k z_{ik}, \quad w_k \geq 0, \quad \sum_k w_k = 1 \quad (7)$$

$$I_i = 1 \quad \text{if } SLMI_i \geq \tau, \min_k z_{ik} \geq \tau_{\min},$$

and audit/additionality pass (8)

$$\text{CreditedTrees}_i = I_i \times \text{AuditedLiveStems}_i \quad (9)$$

Fifth, the species and governance matrices were retained as structured qualitative layers. The species matrix screens 13 native woody and shrub candidates against drought tolerance, salinity tolerance, facilitation potential, establishment practicality, and ecological amplitude. The governance matrix compares seven rehabilitation-relevant provisions of the Mining Investment Law with SER good-practice elements. The mathematical layer therefore does not create pseudo-precision from absent field data; it specifies how future audited observations can be converted into transparent, reproducible landscape-management decisions.

2.4 Quality assurance and methodological limitations

The workflow was controlled by three quality-assurance rules. All quantitative statements in the Results are traceable to a named institutional source or a verified peer-reviewed record and any calculations are identified with rule 1 (source primacy). Rule 2 (dual verification): If

it was possible, the headline figures were compared with an independent statement; if not retrievable, the candidate DOIs and metadata entries were discarded and corrected as appropriate; the current official target formulations were retained as such, along with the date they were retrieved and the program layer label. Both were reported separately and not combined if there were different interim milestones (e.g. the general SGI 2030 policy and the NGP first-phase operational pathway). Rule 3 (assumption transparency): All parameters of the scenario, all decisions in the species matrix about scoring and all qualitative coding decisions are made transparent and can be re-run or challenged by readers.

This design has four methodological limitations that qualify the interpretation. First, it is assumed from international and regional data as there is lack of primary field data and thus is considered as a research priority for the rehabilitation outcomes in the Saudi Mine sites. Secondly, for the Saudi Arabia, the reported forest-area series is a single estimate over time and is not a measured trend, which also limits the potential to infer a trend and supports the call for improved national vegetation accounting [24]. Thirdly, the corporate disclosures do not report disturbed/rehabilitated area at the site-level and the scenario area envelope is added to the national pathway, not to audited mine-site footprints. Fourth, grey-literature targets are policy commitments which can be revised; the study gives full notice of the date of each target statement and reports coexisting formulations, without silently reconciling them.

3 Results

3.1 Forest baseline and green-initiative progress in Saudi Arabia

The verified international series has reported forest area as 9,770 km² in Saudi Arabia, which is 0.4545% of the total land area of Saudi Arabia (2,149,690 km²) and has not been changed for the years 1990–2022 [24]. The static series doesn't mean vegetation cover is literally unchanged, but rather it is a reflection of limitations of the international reporting series for rehabilitation outside the traditional forest category. More than 159 million trees have been planted and more than 1.0 million ha of degraded lands recovered by early 2026 (based on official Saudi reporting [31]). There are therefore three policy levels which have been reported over time, each depicted in Figure 1: (i) current progress; (ii) the National Greening Program (operational phase one until 2030: 215 Million trees and 2.5 Million hectares); and (iii) broader SGI policy points (2022–2024 policy statement >600 Million trees by 2030 and long-term target of 10 Billion trees linked to 40 Million hectares). Based on this, 159-million trees is approximately 74.0% of operational pathway (215-million); 26.5% of policy reference

(600-million); 1.59% of long term (10-billion); and 1.0-million restored hectares is 40% of operational pathway (2.5-million); 2.5% of long term (approx. 40-million hectares). This multi-layered approach doesn't assume that the different stages of the programme are a single denominator.

3.2 Mining sector profile, growth, and the degraded-land portfolio

Table 1 describes the eight major operating mines which support the Saudi mining sector: five gold mines (Mahd Adh Dhahab underground, Bulghah open-pit, Sukhaybarat open-pit (co-operated with Bulghah), Al Amar underground (copper–zinc concentrates), and Ad Duwayhi open-pit), one phosphate mine (Hazm Al-Jalamid open-pit with downstream complex) and two bauxite mines (Al Ba'itha – the only metallurgical bauxite operation in the region – and Az Zabirah for low-grade bauxite and kaolin) [39]. Geographic fixability of a site is the structure that makes it a rehabilitation asset class that is tractable and monitorable, and is directed at large waste streams (waste-rock dumps, tailings storage facilities, heap-leach pads, pumped tailings beaches etc.). Figure 2 presents verified production growth of the sector between 2018 and 2024; it shows that gold production grew from 414.966 thousand ounces to 495 thousand ounces (computed CAGR +2.98%), primary aluminium production increased from 932.209 thousand tonnes to 986 thousand tonnes (computed CAGR +0.94%) and phosphate production increased from 3.17 million tonnes to 6.19 million tonnes (computed CAGR +11.80%).

The gold production grew by 21% year-on-year in 2023 to 407 thousand ounces, while the production of aluminium fell by 6% to 895 thousand tonnes and the production of phosphate fertilizer rose by 15% to 5.899 million tonnes in record 9.099 million tonnes of total phosphate production [40]. This trend continued in 2024 and saw further growth in gold (+21.6% to 495 thousand ounces), aluminium (+10.2% to 986 thousand tonnes) and fertilizer (+4.9% to 6.19 million tonnes) [39]. Table 2 brings together these and the program-level indicators along with sources. The direction of travel is clear – all the major commodity lines are already on a big base, and with Vision 2030's ambition of mining as the third pillar of the economy – and an estimated mineral endowment of approximately SAR 9.4 trillion [37] – the disturbed-land portfolio will continue to grow, unless that progress is built into operations from the start.

3.3 Synthesis of rehabilitation evidence and its arid-zone transferability

Figure 3 is a compile of the verified quantitative anchors from the synthesis. The largest meta-analysis of forest

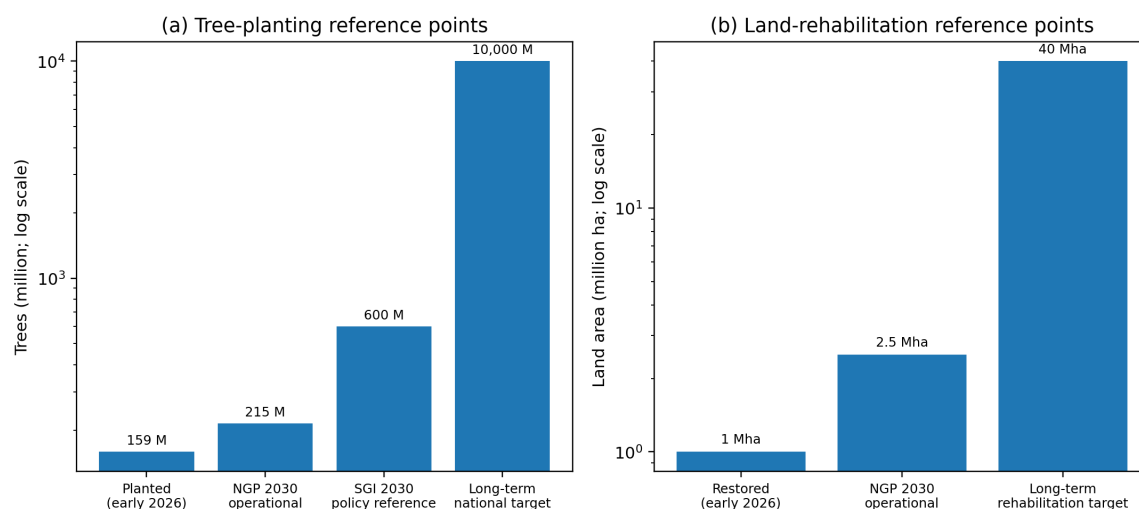


Fig. 1: Saudi greening progress and distinct program reference points (logarithmic scales). (a) By early 2026, the number of trees planted is more than 159 million; the National Greening Program (NGP) first-phase operational pathway is 215 million trees by 2030; the broader SGI policy reference is more than 600 million trees by 2030; and the long-term national target is 10 billion trees. The current long-term rehabilitation target of ~40 million hectares; the NGP 2030 operational pathway of 2.5 million hectares by early 2026; and (b) 1.0 million hectares by early 2026. Sources: Saudi Green Initiative [30]; Ministry of Environment, Water and Agriculture [31]; Saudi Press Agency [32].

Table 1: Major operating mines of the Saudi mining sector and their rehabilitation-relevant characteristics.

Operation	Commodity	Mine type / processing	Business unit	Status
Mahd Adh Dhahab	Gold (doré; historic silver by-product)	Underground mine with CIL plant	MGBM	Operating; modern underground production from 1988
Bulghah	Gold	Open-pit heap leach; higher-grade ore trucked to Sukhaybarat	MGBM	Operating
Sukhaybarat	Gold	Open-pit mine with CIL plant	MGBM	Operating; reported jointly with Bulghah
Al Amar	Gold with copper and zinc concentrates	Underground mine with CIL plant	MGBM	Operating; production from 2009
Ad Duwayhi	Gold	Open-pit mine with CIL plant	MGBM	Operating; production from 2016
Hazm	Phosphate rock concentrate	Open-pit mine with beneficiation plant	MPC	Operating; feeds Wa'ad Al Shamal / Ras Al-Khair
Al Ba'itha	Bauxite (metallurgical)	Open-pit mine; ore railed to Ras Al-Khair refinery	MBAC	Operating; region's only bauxite mine
Az Zabirah	Low-grade bauxite and kaolin	Open-pit mine	MIMC	Operating; bauxite to cement industry

Note: Compiled from Ma'aden [39]. CIL, carbon-in-leach; MGBM, Ma'aden Gold and Base Metals Company; MPC, Ma'aden Phosphate Company; MBAC, Ma'aden Bauxite and Alumina Company; MIMC, Ma'aden Industrial Minerals Company. Site-level disturbed areas are not publicly reported (see Section 3.7).

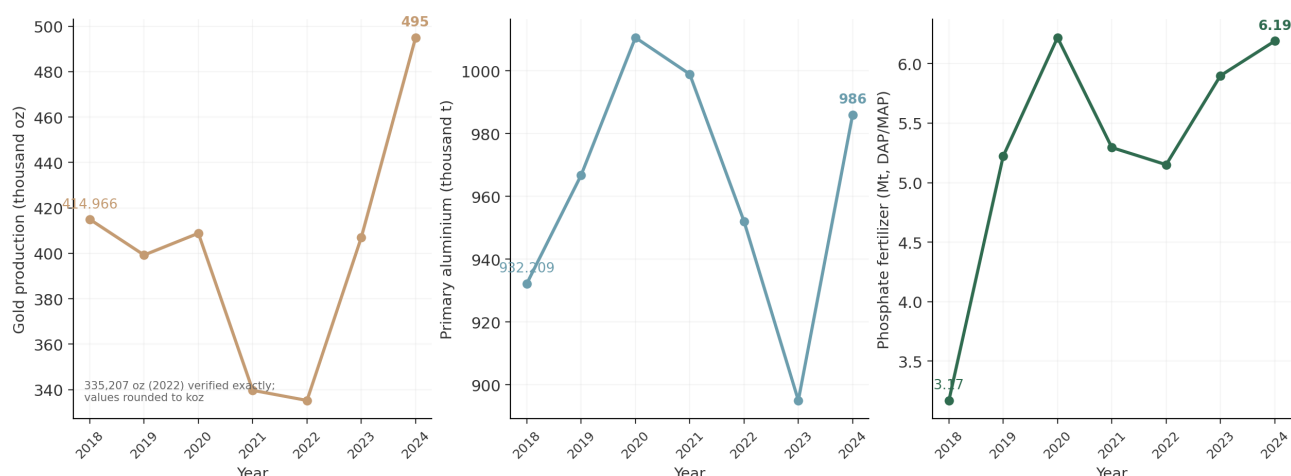


Fig. 2: Verified annual production of the Saudi mining sector, 2018–2024: (a) gold (thousand ounces; 2022 value of 335,207 oz verified exactly, series rounded to thousand ounces); (b) primary aluminum (thousand tonnes); (c) phosphate fertilizer, DAP/MAP (million tonnes). Data from Ma’aden Board of Directors’ reports [39,40].

Table 2: Verified indicators of the Saudi mining sector and its green-transition coupling, 2022–2026.

Indicator	Value	Reference period	Source
Gold production (Ma’aden)	407 thousand oz (+21% YoY)	2023	Ma’aden (2024) [40]
Gold production	495 thousand oz	2024	Ma’aden [39]
Primary aluminum	895 thousand t (−6% YoY)	2023	Ma’aden (2024) [40]
Phosphate fertilizer (DAP/MAP)	5.899 Mt (+15% YoY); total phosphate products 9.099 Mt (record)	2023	Ma’aden (2024) [40]
Estimated mineral wealth	≈ SAR 9.4 trillion (≈ USD 2.5 trillion)	2024 estimate	Vision 2030 (n.d.) [37]
Cumulative trees planted (SGI)	> 159 million	early 2026	MEWA (2026) [31]
Degraded land restored	1.0 million ha (2.5 Mha planned by 2030)	early 2026	MEWA (2026)
National afforestation target	10 billion trees; rehabilitation commitment > 74 Mha	2030s horizon	Saudi Green Initiative (n.d.); MEWA (2026) [31]
Official forest area	9,770 km ² (0.45% of land area)	1990–2022	World Bank [24]

Note: YoY, year-over-year; Mha, million hectares; DAP/MAP, diammonium/monoammonium phosphate. All values as reported by the cited institutional sources; computed growth rates are given in Section 3.2 and labeled as calculations.

restoration success that has been conducted at the global scale (221 study landscapes) states that at the global scale, the impact of forest restoration on biodiversity is 15–84% and for vegetation structure 36–77% relative to degraded baselines [5]. These ranges are representative of the experiences of forest restoration around the world, not expected outcomes for mine sites in Saudi Arabia. They provide evidence of the size and diversity of reported restoration responses and remind of the importance of site-level monitoring prior to transfer to hyper-arid mine landscapes [42]. On the degradation side, the same evidence suggests that rehabilitation cannot be an after-thought; that mining accounts for 9% of Amazon deforestation (impact far greater than the area of the

lease); and that up to 40% of all the land surface in the world has been degraded [1].

With regards to mine sites in particular, the literature that was retained was able to form four strong qualitative findings. The first binding constraint is called substrate amelioration; the soil of a mine is lacking structure, organic matter and microbial function and the re-establishment of a functioning soil profile is a multi-decadal process that can be quantified by a mine-soil quality index [19, 43]. Secondly, biological interventions help to speed up recoveries – chronosequence evidence demonstrates measurable rebuilding of carbon, nitrogen, phosphorus stock in 8 years of forestation [44]; and biochar amendment shows promise as a reclamation tool for spoil substrates [45].

Third, engineering is not the sole means of achieving goals: When early-seral community is compatible with the target, natural succession may be an alternative reclamation method with reduced costs [20]; and In water limited settings, ecological processes are important because nurse-plant facilitation is a key process in establishing the target species [36]. Fourthly, fauna must be a part of monitoring, as fauna reintroduction is clearly a quality measure for rehabilitation [22] and landscape-function dust suppression directly impacts on policy in drylands [28]. In this evidence base the measurement practice is the finding.

However, vegetation structure continues to be over-used in reviews of restoration evaluation, fauna and soil-function indicators are under-used and few report against explicit reference conditions [14, 15]. The international standards now require recovery trajectories (five star grades) based on a reference ecosystem, and the higher grades require self-organization and ecological function and not just plant establishment [4]. To fill this measurement gap in Saudi context a KPI framework is developed, specifically in Section 3.7. But, an important transferability gap in the synthesis exists as well. Most of the Saudi mining regions receive less than 100 mm per year, which is far less than the quantitative survival, growth and soil-carbon benchmarks, which are mostly based on mesic subtropical and tropical mine sites, and Mediterranean drylands with 300–500 mm per year of rainfall [17, 18, 34, 35]. Site preparation techniques, such as irrigation for establishment and bedding for gypsum substrates [35] will not simply transfer. Thus, evidence indicates that, in theory, arid mine rehabilitation is possible, but that data from trials conducted in Arabia should be a high priority for near-term research funding, affirming international standards that require a site-specific approach to success criteria [4] and the call for a restorative culture and the institutionalisation of ecological recovery as a basic output of business mining by companies [23].

3.4 Candidate native species matrix for mine-land rehabilitation

Table 3 lists the 13 species considered as potential natives and their suitability for screening based on growth form and indicator reliability. Three species have verified evidence of their species from Saudi research: *Vachellia tortilis* (syn. *Acacia tortilis* for which the community level population structure and the regeneration status have been evaluated in the Makkah-region [46]; *Juniperus procera* for which dieback has been correlated with elevation, climate and soils in the southwestern highlands, and regeneration requires matching provenance to site [25]; and *Haloxylon persicum* for which the population ecology has been documented in managed areas in Al-Qassim [47]. The remaining ten species

(*Acacia origena*, *Haloxylon salicornicum*, *Ziziphus spina-christi*, *Tamarix aphylla*, *Prosopis cineraria*, *Salvadora persica*, *Rhanterium epapposum*, *Calligonum comosum*, *Acacia ehrenbergiana* and *Maerua crassifolia*) are added for documented regional occurrence and proven role in dryland restoration, with this fact stated explicitly in the table. The following are two design principles. It is crucial to distinguish highland and lowland portfolios: *J. procera* is limited to the highland (>1500 m) in the belt of Asir-Sarawat while the assemblage of *Acacia-Haloxylon-Rhanterium* is appropriate for the mining districts in the central and northern parts. Two of the ten golden rules for reforestation [13] are: native-species-first selection and invasiveness is a screening criterion; the non-native *Prosopis juliflora* has been observed to sequester soil carbon rapidly on mine sites in other parts of the world [44] and is therefore deliberately not included in the list of candidate species.

That the matrix effectiveness is dependent on the provenance and propagation used. Seed should come from similar bioclimatic zones and documented provenances; when elevation-based genetic differentiation exists, establishment failures are likely to result when seed zones are disregarded [25]. In drought years (low rainfall), materially outplanting survival is increased by dryland practice of nursery preconditioning (decreased irrigation cycles and sun hardening) [34]. Direct seeding following rain on this sand stabilized can be an option in addition to seedlings planting, where seed is available, for sand-stabilizing species (*H. persicum*, *H. salicornicum* and *C. comosum*); the seeds of palatable species (*V. tortilis*, and *R. epapposum*) can also be used as fodder for grazing agreements with local communities [27, 46]. This aspect of the rehabilitation pathway is an employment generating aspect of the establishment of this supply chain, seed zones, nurseries and trained crews [3].

3.5 A rehabilitation-to-afforestation integration framework

The sustainable landscape-management framework acquired in this study is represented as four coupled lanes as shown in Figure 4. Lane A sets the lifecycle of mining activities – exploration, exploitation, processing and progressive closure – in the setting of the Mining Investment Law and its licenses, which are linked to rehabilitation obligations of the operating companies [38]. Lane B states that the rehabilitation system is comprised of three interdependent areas: soil reconstruction using techniques summarized in the literature (Section 3.3); selection of native species, using the matrix for nursery plant selection (Table 3); and water and microclimate manipulation using rainwater harvesting structures, bedding materials and mulching. Lane C is the verification portion and includes the success criteria, long-term monitoring and independent audit of

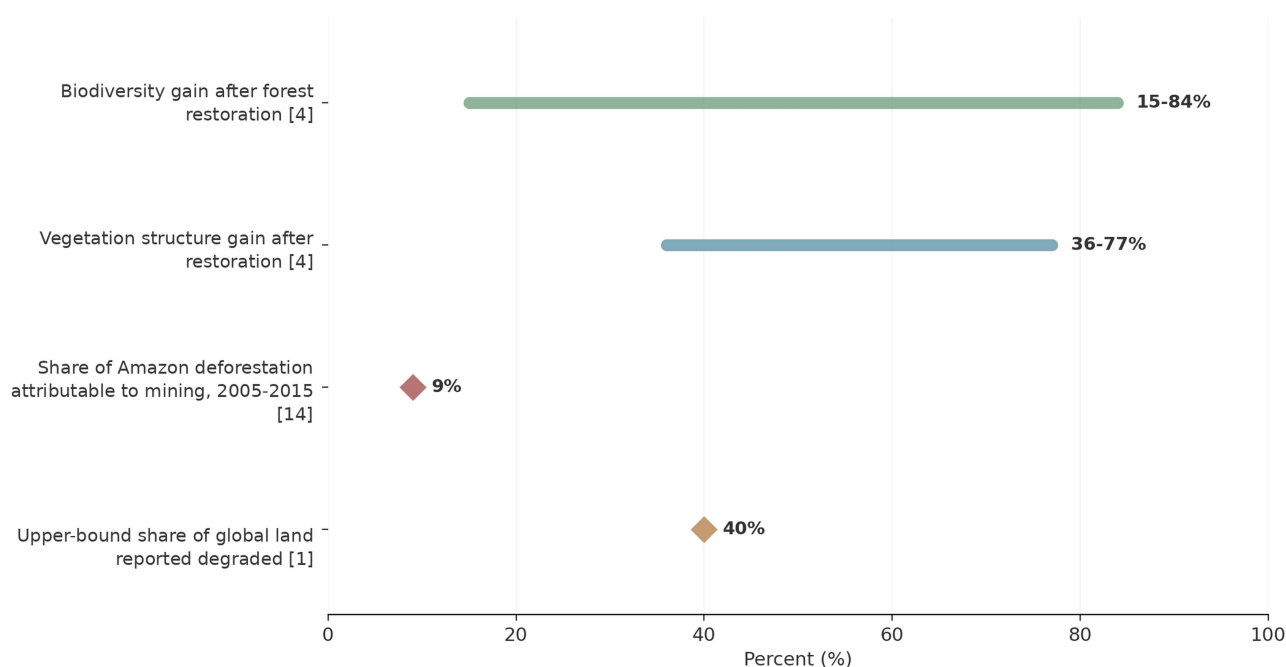


Fig. 3: Key quantitative anchors from the verified evidence synthesis: biodiversity and vegetation-structure gains following forest restoration in a 221-landscape global meta-analysis [5]; the mining-attributable share of Amazon deforestation, 2005–2015 [16]; and the upper-bound share of global land reported degraded [1].

certified rehabilitated land, and financial assurance release. The circle is completed with national accounting, where only the certified land and verified tree counts and rehabilitated hectares can be counted towards SGI and Land Degradation Neutrality (LDN) reporting. The additionality rule is the most important governance innovation within the framework as it removes the risk of double counting to the integrity of national targets whilst delivering a legally clear asset to operators – certified restoration outcomes – for their sustainability disclosures [4, 23].

3.6 Scenario estimates of mine-land contributions to national targets

The calculated scenario envelope according to the procedure of Section 2.3 is presented in Figure 5. The conservative scenario ($5,000 \text{ ha yr}^{-1}$ at $400 \text{ stems ha}^{-1}$) grows 28 million trees on 70,000 ha rehabilitated by 2040; the moderate scenario ($10,000 \text{ ha yr}^{-1}$ at $600 \text{ stems ha}^{-1}$) grows 84 million trees on 140,000 ha rehabilitated by 2040; the ambitious scenario ($20,000 \text{ ha yr}^{-1}$ at $800 \text{ stems ha}^{-1}$) grows 224 million trees on 280,000 ha rehabilitated by 2040. The verified national reference points (NRPs), which the 2040 envelope is relative to, represent 0.28–2.24% of the 10-billion-tree target. For scale comparisons, this would be 2040 totals; they are equivalent to between 4.7–37.3%

of the historical 2030 policy target of 600 million trees. These scenarios equate to between 8 and 64 million gross planted stems over 2027–2030, 3.7–29.8% of NGP's operational pathway, and 1.3–10.7% of the broader policy context (600 million stems). The small area of 20,000–80,000 ha can be added at a small number of sites, where additionality can be shown, reporting can be audited and where there is already corporate finance for the 2.5-million-ha NGP 2030 pathway. There are three features of these estimates which deserve special mention. They are conservative (deliberately so) in terms of area, when compared to the growth of the mining sector; they are low-input, compatible with water-limited establishment [12, 13]; and they are traceable end-to-end, with all parameters explicitly given in Section 2.3, rather than hidden in an opaque model.

3.7 Sensitivity analysis and quantitative sustainable landscape-management decision rules

The entire 3×3 factorial sensitivity matrix (Table 5; Figure 6) decouples the two scenario drivers. Over 2027–2040, gross planting potential ranges from 28 million stems ($5,000 \text{ ha yr}^{-1} \times 400 \text{ stems ha}^{-1}$) to 224 million stems ($20,000 \text{ ha yr}^{-1} \times 800 \text{ stems ha}^{-1}$). Intermediate combinations demonstrate that the

Table 3: Candidate native species matrix for mine-land rehabilitation in Saudi Arabia, with declared evidence basis.

Species	Family	Growth form	Key tolerance / trait	Restoration role	Evidence basis
<i>Vachellia tortilis</i> (syn. <i>Acacia tortilis</i>)	Fabaceae	Evergreen tree	Drought and heat tolerance; nitrogen fixer	Nurse tree; fodder; rangeland agroforestry	Population study, Makkah region [46]
<i>Acacia ehrenbergiana</i>	Fabaceae	Shrub / small tree	Severe drought; resprouting ability	Nurse shrub; erosion control	Regional floristic occurrence*
<i>Acacia origena</i>	Fabaceae	Tree	Highland fog interception	Highland restoration (Asir–Sarawat)	Regional floristic occurrence*
<i>Juniperus procera</i>	Cupressaceae	Conifer tree	Elevation-linked dieback sensitivity	Highland afforestation; provenance matching required	Dieback and restoration study [25]
<i>Haloxylon persicum</i>	Amaranthaceae	Shrub	Psammophyte; sand stabilization	Dune fixation; sandy substrates	Population ecology, Al-Qassim [47]
<i>Haloxylon salicornicum</i>	Amaranthaceae	Shrub	Drought and sandy saline soils	Rangeland rehabilitation; cover rebuilding	Regional floristic occurrence*
<i>Ziziphus spina-christi</i>	Rhamnaceae	Evergreen tree	Heat and salinity tolerance; deep roots	Agroforestry; shade; deep-soil sites	Regional floristic occurrence*
<i>Tamarix aphylla</i>	Tamaricaceae	Evergreen tree	Salinity and aridity; phreatophyte	Saline-site amelioration; windbreaks	Regional floristic occurrence*
<i>Prosopis cineraria</i>	Fabaceae	Tree	Drought; deep taproot; non-invasive native	Fodder; shade; native alternative to <i>P. juliflora</i>	Regional floristic occurrence*
<i>Salvadora persica</i>	Salvadoraceae	Shrub / tree	Salinity tolerance	Marginal-land greening	Regional floristic occurrence*
<i>Rhanterium epapposum</i>	Asteraceae	Dwarf shrub	Sandy soils; palatable forage	Understory cover; dust suppression	Regional floristic occurrence*
<i>Calligonum comosum</i>	Polygonaceae	Shrub	Mobile-sand specialist	Dune fixation	Regional floristic occurrence*
<i>Maerua crassifolia</i>	Capparaceae	Tree	Extreme-aridity survivor	Drought refugia; nurse tree	Regional floristic occurrence*

Note: *Regional floristic occurrence: species presence is documented in national vegetation records and dryland restoration practice, but site-specific performance data on rehabilitated mine land in Saudi Arabia are not yet published (evidence gap identified in Section 3.3). The non-native *Prosopis juliflora* is excluded from the candidate pool on invasiveness grounds notwithstanding its documented soil-carbon performance on mine spoil elsewhere [44].

elasticities of density and area are the same in the deterministic model. This is beneficial for planning as it exposes the trade-offs: a proportional increase in the rehabilitated area leads to the same increase in the gross stem count, and a proportional decrease in the water availability leads to the same decrease in the gross stem count. The model does not represent, however, ecological success as equal to planted stems. Crediting takes place only following field monitoring, certification and the additionality test in Eqs. (8)–(9).

Figure 7 translates the SLMI into a governance-compatible decision architecture. The index is not proposed as a substitute for ecological judgment; rather, it is a reproducible audit layer. A site can fail certification even with a high composite SLMI if any critical domain falls below $\tau_{\min}$, or if the

additionality/audit gate fails. This non-compensatory safeguard is particularly important in mine closure, where strong planting performance cannot legitimately offset unstable landforms, contaminant risks, or absent governance evidence.

3.8 Governance readiness and the monitoring KPI framework

Table 6 provides a comparison between the pertinent features of the Saudi Mining Investment Law (SMIL) on rehabilitation and international standards about SER. The comparison indicates the need for legal scaffolding, but not yet sufficient: Ecologically meaningful completion criteria, standardized long-term monitoring and public

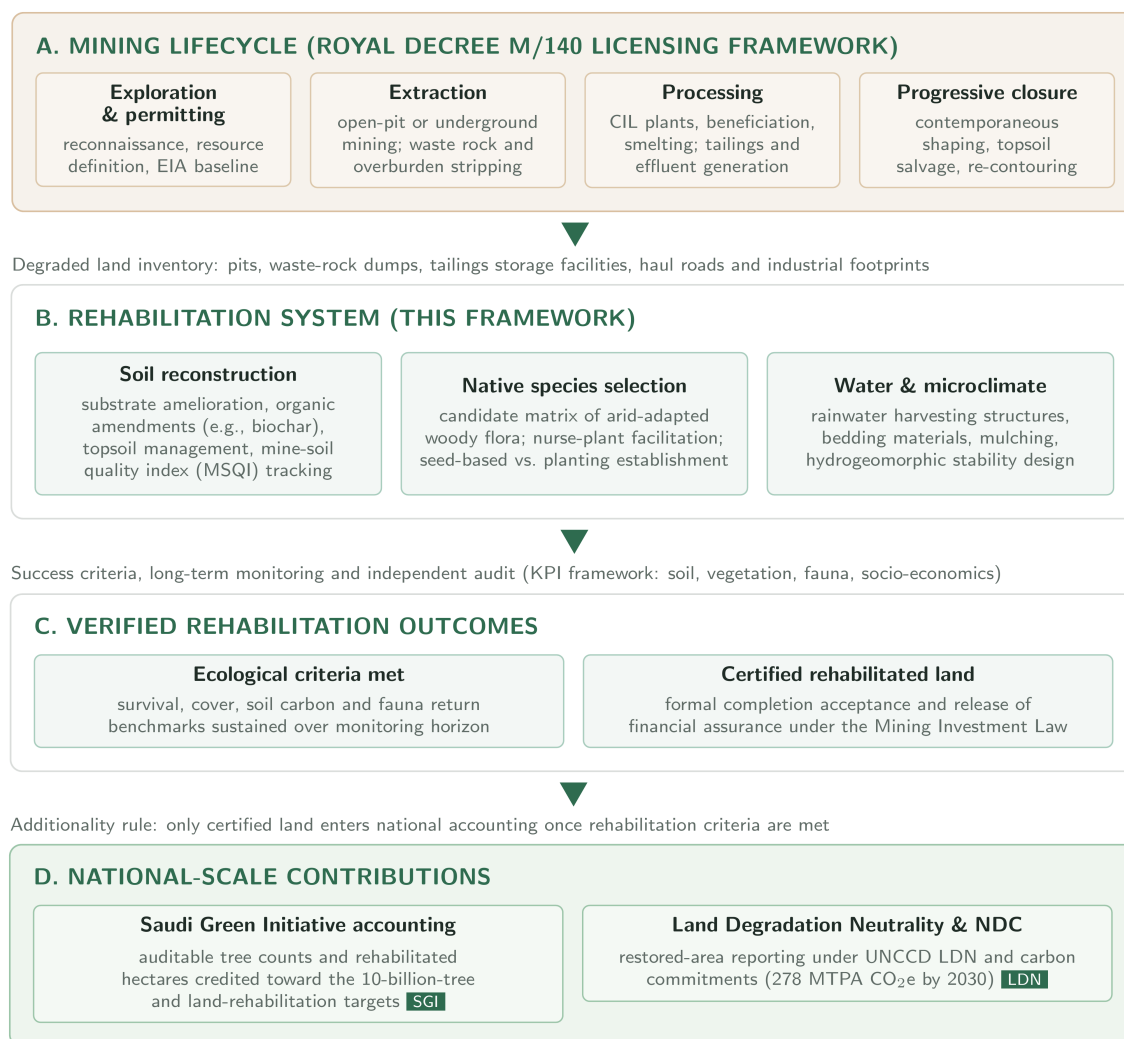


Fig. 4: Sustainable landscape-management framework integrating mine-site rehabilitation with national afforestation accounting. Lane A: mining lifecycle under the licensing framework of Royal Decree M/140 [38]. Lane B: three-domain rehabilitation system developed in this study. Lane C: verification layer producing certified rehabilitated land. Lane D: additionality-gated contributions to Saudi Green Initiative and Land Degradation Neutrality accounting.

disclosure on the site-level are not yet addressed in the implementing instruments and are part of international good practice [4]. This can be observed through a concrete disclosure gap; The full-text search on the two cited Ma'aden Board reports did not yield any disclosure on the area (in hectares) of land disturbed or land rehabilitated, but a detailed production disclosure is found in Section 3.2 [39, 40]. Table 7 operationalizes the monitoring layer by providing its seven domains (soil development, amendments, vegetation, fauna, landscape function, socio-economics, governance) and protocols and illustrative benchmarks based on the verified literature [3, 5, 19, 22, 28, 34, 44, 45]. Having certified mine rehabilitation along with reporting of Land

Degradation Neutrality makes the case even more compelling. The UNCCD's global framing assumes that 1.5 billion hectares will be restored by 2030, and that to be effective, national LDN strategies should be based on spatially explicit, monitored actions – and not on aggregate pledges [1]. But mine sites do a very good job of meeting both of these criteria: they have their footprint mapped, the operators have licences with reporting requirements [38] and the outcomes of restoration can be contractually audited. In the economic literature on restoration under the Bonn Challenge, the complementary argument is that finance for restoration can be most easily raised where there is overlapping between land tenure,

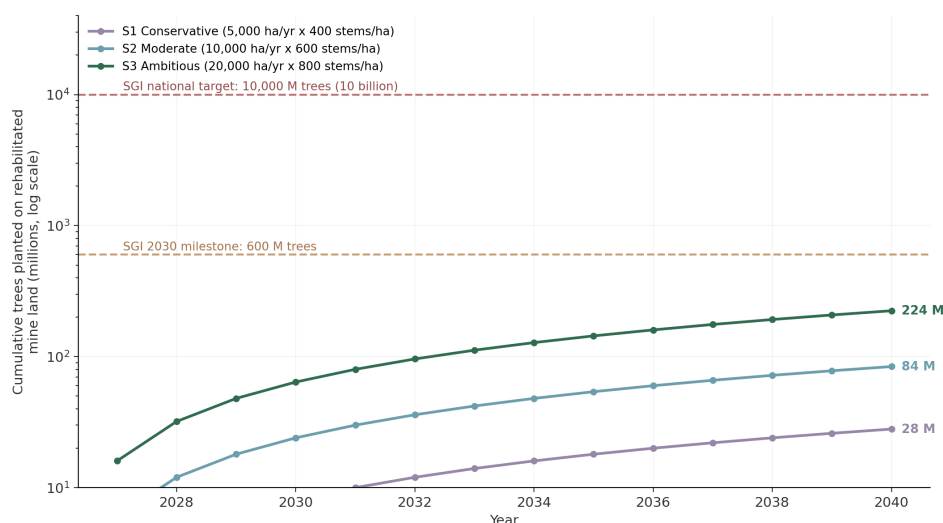


Fig. 5: Scenario envelope of cumulative gross tree planting on rehabilitated mine land, 2027–2040, under three paired parameter sets defined in Section 2.3 (conservative S1, moderate S2, ambitious S3), shown against the historical SGI 2030 policy reference of 600 million trees and the 10-billion-tree long-term national target. Values are illustrative planning magnitudes, not forecasts or certified outcomes; Table 5 and Figure 6 provide the full factorial sensitivity analysis.

Table 4: Quantitative model components used in the sustainable landscape-management framework.

Component	Expression	Interpretation
Growth accounting	$YoY(t) = 100 \frac{V(t) - V(t-1)}{V(t-1)}$; $CAGR = \left[\frac{V(2024)}{V(2018)} \right]^{1/6} - 1$	Describes production change without causal inference
Planting potential	$T(s, H) = \sum_t A(s, t) D(s, t)$	Gross planted stems; not survival-adjusted
Target contribution	$C(s) = 100 T(s) / T_{ref}$; $L(s) = 100 \sum_t A(s, t) / A_{ref}$	Scale relative to explicitly dated policy reference
Indicator normalization	$z_{ik} \in [0, 1]$ using benefit/adverse min–max rules	Puts heterogeneous KPI domains on common scale
Composite performance	$SLMI_i = \sum_k w_k z_{ik}$; $\sum_k w_k = 1$	Transparent multi-criteria landscape-performance score
Certification gate	$I_i = 1$ only if score, minimum-domain, audit, and additionality criteria pass	Prevents compensatory scoring and double counting
Credited outcome	$CreditedTrees_i = I_i \times AuditedLiveStems_i$	Separates planting activity from verified national-accounting outcome

Table 5: Full-factorial sensitivity matrix of cumulative gross planted stems by 2040 (million stems; $H = 14$ years).

Annual area (ha yr ⁻¹)	Planting density		
	400 stems ha ⁻¹	600 stems ha ⁻¹	800 stems ha ⁻¹
5,000	28	42	56
10,000	56	84	112
20,000	112	168	224

capacity to implement, and measurable outputs – which by construction is the case on licensed mine land.

4 Discussion

4.1 Principal findings in global context

Four main conclusions are drawn. First the scale of planting Saudi Arabia is trying to achieve with its restoration program has now become so large that the quality of the accounting is now the limiting factor: so far, by early 2026, 159 million trees and one million hectares have been planted, reported, audited and verified [29, 31]. This makes mine rehabilitation attractive because it is

Table 6: Rehabilitation governance elements: the Saudi Mining Investment Law compared with international good practice.

Governance element	Saudi Mining Investment Law (Royal Decree M/140)	International good practice (SER standards)
Licence architecture	Separate licence classes (exploration, mining lease, small-scale) with defined terms, work programs, and performance obligations	Licences conditioned on ecological outcomes, not only extraction performance
Environmental obligations	Environmental studies, protection, and compliance obligations embedded in licensing	Site-specific success criteria tied to reference ecosystems (five-star system)
Financial assurance	Guarantees securing performance of licence obligations	Assurance sized to full third-party rehabilitation cost; released only on certified completion
Completion criteria	Left to implementing instruments and operator plans; no ecologically explicit criteria in the law text	Quantified, independently auditable completion criteria agreed before closure
Progressive rehabilitation	Work-program obligations provide a hook; contemporaneous reclamation not explicitly mandated	Progressive rehabilitation during operations is the default expectation
Monitoring and reporting	Periodic reporting duties to the Ministry	Long-term monitoring with public reporting across soil, vegetation, fauna, and function
Public disclosure	Site-level disturbed/rehabilitated areas not reported in current corporate disclosures	Standardized ESG disclosure of disturbed and certified-rehabilitated hectares

Note: Qualitative document analysis based on the official English text of the Mining Investment Law [38] and the SER international standards [4]; the disclosure row reflects the full-text search of the two cited Ma'aden Board reports described in Section 3.7. The comparison is indicative and does not constitute legal advice.

Table 7: Key-performance-indicator framework for monitoring mine-land rehabilitation in arid Saudi Arabia.

Domain	Indicator	Measurement protocol	Illustrative benchmark / target	Supporting literature
Soil development	Mine-soil quality index (MSQI); soil organic C and total N stocks; EC, pH, bulk density	Permanent-plot chronosequence sampling against a reference ecosystem	Trajectory toward reference values within 20–30 years	[19, 44]
Amendments	Amendment dose-response; water-holding capacity; bioavailable metals	Field trials with randomized doses	Site-specific optimal dose identified within 3–5 years	[43, 45]
Vegetation	Seedling survival; canopy cover; species richness; natural regeneration density	Annual survival counts (years 1–5); cover and richness at 5-year intervals	Survival stabilized above dryland practice thresholds; cover trending toward reference	[5, 34]
Fauna	Species occurrence and abundance of indicator taxa	Camera traps, bioacoustics, invertebrate surveys	Progressive return toward reference-site assemblages	[22]
Landscape function	Dust-emission control; hydrological stability (gully density, landform stability)	Remote sensing (vegetation indices) with ground calibration	Reduced downwind dust events; stable landforms	[28]
Socio-economic	Local employment; forage/fodder value; community acceptance	Periodic surveys; licence compliance records	Positive and documented local development outcomes	[3]
Governance	Completion criteria met; financial assurance released; disclosure of disturbed/rehabilitated hectares	Independent audit; standardized ESG reporting	100% of closed areas certified; annual public disclosure	[4, 38]

Note: The framework is designed for phased implementation: survival and compliance indicators are annual; soil, fauna, and landscape indicators are cyclical (3–5 years); benchmarks are illustrative and should be finalized against Arabian trial data (Section 4.5).

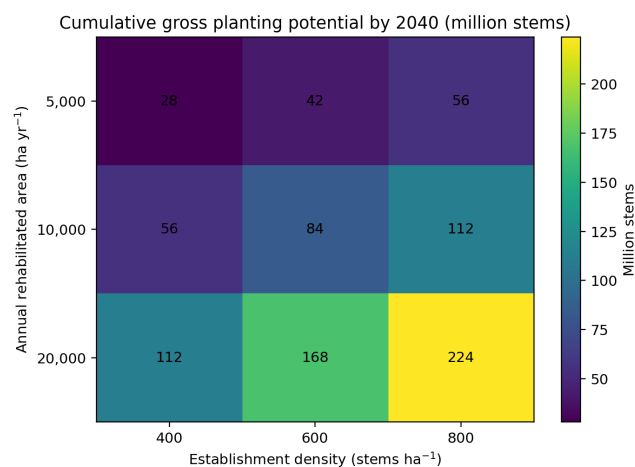


Fig. 6: Deterministic sensitivity surface for cumulative gross planting potential on rehabilitated mine land over 2027–2040. Values are million stems for the full factorial combination of annual rehabilitated area and establishment density. The figure describes planning capacity, not survival-adjusted or certified outcomes.

small (0.3–2.2% of the national target by 2040), it is contractible, fundable and auditable through an existing licensing regime [38]. Second, the evidence from around the world indicates that rehabilitated degraded land can offer significant ecological benefits on a large scale [5, 42] and the mine-rehabilitation literature offers the toolbox of substrates-to-fauna to do this [19, 22, 43, 48]. Third, the conditions at the end of the causal chain—the transferability of quantitative benchmarks to hyper-arid Arabian conditions—are the least certain and this can be addressed with deliberate local experimentation as is done in the adaptive dryland restoration practice [34, 35]. Fourth, a legacy of retrofitting degraded land is a more costly prospect later in the established growth path of the mining sector (Figure 2) and can be a moving target. The framework here is intentionally based on the cautionary school, and is juxtaposed with the international debate on planting versus natural recovery.

Brancalion and Holl [12] and Di Sacco et al. [13] offer advice on the safeguards that underlie our species matrix and our density site matching and density assumptions, which include native species and realistic density, respectively, and Lewis et al. [11] warns about producing low diversity plantations in unsuitable locations. This critique is consistent with the mine-land pathway—that planting takes place in a recovery trajectory, and that it is ecological restoration of land that may need to be restored, either way. The scope for application of the ten golden rules, in the sense of a bounded, owned and managed land base in which the competing food production and conservation trade-offs can be avoided, is unique and rare in this context. It is

also helpful to see the scenario envelope in the context of the national restoration programme of which it is a part. The 20,000 ha yr⁻¹ in the ambitious scenario represents 0.8% of the 2.5 million ha already reported for restoration in 2030 [31] and thus will not require a rewriting of the national programme. Thus, the binding constraints on the envelope are not physical, but institutional: certificate throughput and supply of native-seeds, and monitoring bandwidth [4, 12]. This study is in line with the literature on plantings guidance that mostly indicates that biological and governance aspects, and not land availability, are the dominant issues in large plantings [13].

4.2 Biophysical feasibility and constraints in hyper-arid systems

The master variable is water. The success of establishment in drylands depends on the balance between the demand for water by the plants and the amount of water harvested or available naturally, thus the dryland restoration practice focuses on water-harvesting micro catchments, lower plant densities, drought-screened provenances, and phased planting with the wet seasons [34]. The realistic establishment model for Saudi mining districts is to use nursery-raised seedlings of the lowland assemblage (Table 3) and plant pits aligned with the contours that incorporate gravel mulching, and nurse-shrub facilitation to reduce vapor-pressure deficits (VPD), as indicated in the facilitation evidence for degraded dry environments [36]. Establishment via irrigation should rather be considered as a phase out subsidy in line with the water-budget realities. A second class of constraints are called substrate conditions. The typical characteristics of tailings and processed spoil are: compaction; absence of structure; increase in salinity; and in gold districts, possible increase in metalloid content. Amendment literature offers a menu of options: use of organic matter in combination with soil, topsoil salvage and reinstatement, and biochar use to increase water holding capacity and to reduce bioavailable toxicity [43, 45]; and rhizosphere literature cautions that well-designed root zone cannot replace the need for stable landform design [18]. It is important to note that the most appropriate choice of plant is for phytostabilization and not phytoextraction, for arid tailings [17].

The biotic pressures make up the whole picture. Elsewhere in western Saudi Arabia, open grazing has been found to reduce rangeland diversity and to simplify its composition over decades, and livestock exclusion has been measured as a recovery [26]; and to date, grazing by camels and sheep has an impact on vegetation cover in northern rangelands [27]. Therefore, grazing exclusion fencing and grazing management agreements with the local rightsholders should be a standard design component of rehabilitation sites, rather than a “nice to have”. Policy co-benefit: The land surfaces are stabilized

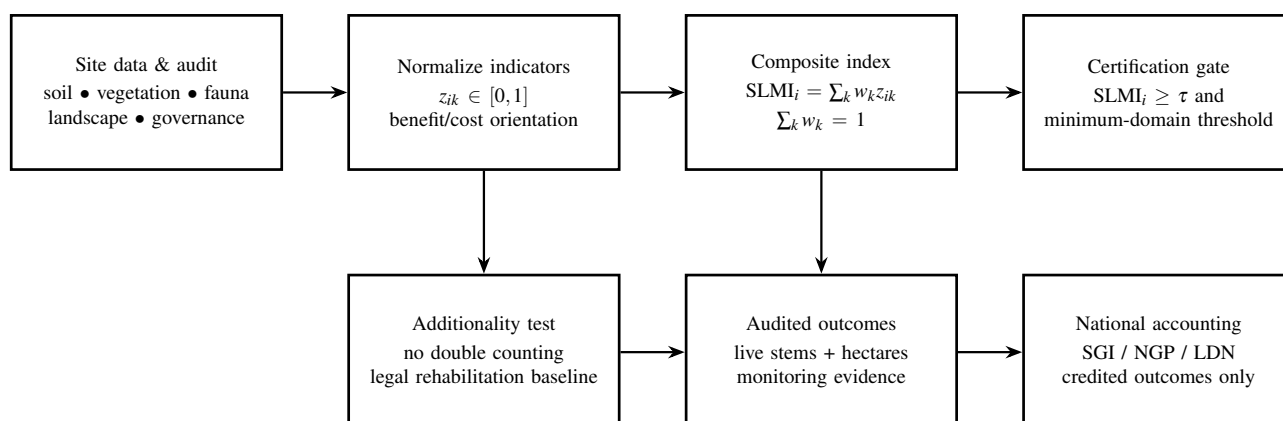


Fig. 7: Quantitative sustainable landscape-management certification architecture. Monitoring indicators are normalized, aggregated into the SLMI, subjected to composite and minimum-domain thresholds, and then passed through independent audit and additionality gates before any live stems or rehabilitated hectares can be credited to national reporting.

around the mine site, which can be measured by the reduction of dust events downwind. Finally, species selection should be climate conscious because the species *Juniperus procera*, which is sensitive to elevation and climate and is experiencing dieback at some sites [25] would benefit from a provenance test based on future warm and dry climate rather than historical distribution.

4.3 Economic and institutional enablers

The economics of mine rehabilitation are good for early action as the costs are primarily earthworks and amendments, and these can be cost-effective if they can be achieved in parallel with operations when fleets and staff are in place and landforms are still being created. The benefit–cost rationale can be seen in the amount of literature about restoration-finance that shows that avoided degradation and early rehabilitation clearly dominates delayed restoration. That same intertemporal logic is the basis for the economic argument that underlies the Bonn Challenge itself, which calls for net benefits valued in the trillions of dollars over the course of the pledges [3]. There are 3 institutional levers available for Saudi operators. The Mining Investment Law requires that certain studies be conducted as well as environmental protection duties, and calls for financial guarantees of the fulfilment of licence obligations, which sets out the legal framework for progressive-rehabilitation schedules [38]. The disclosure infrastructure for production is complex, and the introduction of the hectares disturbed and the hectares certified-rehabilitated has a small change but great credibility impact [39, 40]. The SGI is the demand side and a national accounting system is thirsty for auditable green results [29]. What is missing is the connective tissue—the certification standards, completion criteria and accounting rules—this is what the framework

of Figure 4 and Tables 6 and 7 provide. Consideration of two financing mechanisms is needed in particular. Bonds associated with the cost of the rehabilitation (progressive rehabilitation bonds) impose the obligation of closing in the economics of operations and remove the incentive to defer [4, 38]. Second, outcome linked crediting: certified hectares and trees can be given a verifiable outcome premium in ESG disclosure and in voluntary carbon and land degradation markets if certified using conservative monitored stock change methods that are consistent with the soil-development indicators in Table 7 [3, 4]. The chronosequence literature offers a measurement system for such claims [19, 44] and amendment based establishment brings in cost efficiency in the short term when amelioration of the spoil is required [45].

4.4 Implications for applied mathematical decision support and sustainable landscape management

A study of quantitative contribution that is parsimonious. The multiplicative scenario model allows one to identify two management levers that can be directly manipulated – planting area per year and establishment density – as well as the SLMI formalizes the multidimensional conditions for the use of planting as successful landscape rehabilitation. The distinction is essential for information-science and decision support applications, where activity data – the number of hectares treated, the number of stems planted etc. – is to be supplied to the planning model, while outcome data – how the soil is doing, the vegetation is persisting, fauna is returning, landform is stabilising, social performance and governance evidence etc. – is to be supplied to the certification model. This allows for a digital mine-closure registry or digital dashboard, where the indicator vectors

for each mine are time-stamped, the weights and thresholds are explicitly laid out and the closure of each mine can be audited for certification. Weights can be estimated using stakeholder elicitation or multi-criteria decision methods for future implementations, and, if adequate observations are available at Saudi mine-sites, the deterministic scenario inputs can be replaced by probability distributions. While such observations are not available, deterministic sensitivity analysis is better than fake stochastic precision.

4.5 Policy and management implications

Seven recommendations follow. R1: create national register of degraded-mine-land that includes all pits, dumps, tailing facilities and abandoned workings, which already exists in the form of a consolidated license in Royal Decree M/140 [38]. R2: Embed completion criteria for arid zones in regulations through the SER five star system [4] and the KPI framework (Table 7). R3: develop a native-seed and seedling supply chain for the species listed in Table 3; seed availability is the most frequent early point of failure of restoration programmes worldwide [13]. R4: apply the additionality rule to protect the integrity of the targets, and create a market for certified rehabilitation [1, 29]. R5: Implement progressive rehabilitation schedules during mine work programmes that are part of a phased closure process, and not deferred to the end of life [23, 38]. R6: support a national network of long-term rehabilitation trials that are conducted along rainfall and substrate gradients and have compulsory 10 year monitoring of the Table 7 indicators and public release of the data; directly address the evidence gap identified in Section 3.3 [15, 34]. R7: Develop grazing-management agreements around rehabilitation areas: evidence suggests that exclusion results in recovery, but other grazing-management techniques are required after establishment [26, 27].

4.6 Limitations and future research directions

Beyond the methodological limitations discussed in Section 2.4, there are three research frontiers that could help reduce the risk inherent in the pathway described in this paper. Controlled establishment trials, at different irrigation phase-out scenarios, amendment levels and nurse-plant configurations in the lowland species pool would first replace the imported survival assumption with Arabian benchmarks, and would secondly allow for the species matrix to be shifted from evidence based to evidence graded [34, 36]. Second, if the monitoring of restored hectares was carried out using remote sensing, and correlated to ground plots, the rapidly growing restoration ledger maintained by the SGI could be audited at a national level, and that a contribution of hectares

from a mine site could be reported automatically [28]. Thirdly, research which assessed the value of the ‘bundle of ecosystem services’ delivered by mine rehabilitation, based on the certified approach of dust suppression, forage value, carbon accumulation and cultural value, would benefit the business case in the corporate and treasury decision makers’ language [3, 10]. It is now time to begin the chronosequence approach, the basis of the science of mine-soil rehabilitation [19, 44] at little or no cost by simply establishing plots, which are permanently marked as rehabilitation continues. The fourth priority is the version-controlled policy accounting, because the milestones of Saudi greening have been varying over the years and with the releases of the policies, the date of the release, the level of institution and the level of the policy program in which the denominator of the Saudi greening is included should be preserved. Fifth, statistical calibration of the SLMI thresholds and weights when repeated observations of the sites become available (the current formulation is a transparent decision rule, not an empirically estimated predictive model).

5 Conclusion

This research tested the feasibility of rehabilitation of mining degraded landscapes to work as a complementary auditable pathway in the national greening agenda of Saudi Arabia and created a quantitative sustainable landscape-management framework to do so. This evidence demonstrates proof of principle, but not for the transfer of global restoration benchmarks to hyper-arid Saudi mine sites. A set of mechanisms, indicator families and contextual outcome ranges is provided in the global literature, but needs to be calibrated locally. Official Saudi statistics indicate that progress is being made quickly on greening and that the mining sector is still growing, giving a realistic chance to link closure with the concrete results of land-restoration. The determinate scenario envelope ranges from 28 to 224 million gross planted stems and 70 to 280 thousand rehabilitated hectares in 2040. These are not credited plan values nor outcomes or forecasts. The area–density trade-off is quantified in the 3×3 sensitivity analysis, and the SLMI and certification equations separate out planting activity from measured ecological response. Only outcomes with a composite score and a minimum domain score and independently audited can be counted towards national accounting. Such separation becomes particularly important if policy objectives, strategies for achieving them, and ways of assessing progress are evolving. The Saudi experience illustrates the general thesis that, in dry lands in particular, extractive land can be a more promising starting point for forest management – and thus for rehabilitations – due to the following: property rights are established, the operators are equity holders, monitoring is contractual, and additionality is demonstrable. Research agendas have been clearly formulated and

institutions are in place for action, with no need for high investment local establishment trials, remote-sensing audit systems, and service valuation. The concept of mine closure in the context of the whole concept of greening as a positive, complete cycle would be a first for Saudi Arabia, and a much-needed one that dryland countries around the world will need as they are closing their mines.

Data availability statement

The datasets analyzed in this study are publicly available from the cited institutional sources: World Bank open data indicators (AG.LND.FRST.ZS, AG.LND.FRST.K2, AG.LND.TOTL.K2), the Saudi Green Initiative platform, the Ministry of Environment, Water and Agriculture release of March 2026, Ma'aden 2023 and 2024 Board of Directors' reports, the official English text of the Mining Investment Law, and the UNCCD COP16 narrative. The verified reference metadata compiled during the synthesis and the scenario computation spreadsheet are available from the corresponding author on reasonable request.

Acknowledgements

The authors extend their appreciation to Northern Border University, Saudi Arabia, for supporting this work through project number (NBU-CRP-2026-3021). The authors are thankful to the Deanship of Graduate Studies and Scientific Research at University of Bisha for supporting this work through the Fast-Track Research Support Program.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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