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Plant succession and its optimization on tar-polluted coasts in the Arabian Gulf region

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Summary

Coastal ecosystems in the Arabian Gulf region are under increasing pressures from hostilities and other developmental activities; the region has a long history of crude-oil pollution. Because of the high ambient temperature, oil deposited along the coastline or inland evaporates, leaving a semi-solid tar. In Qatar, to clean up the polluted sites, the deposited tar is stripped off and dumped in the coastal marshes as confluent dome-shaped piles. Flowering plant colonization of tar-piles is described here as a chronosequence, ranging in age from 2 to 14 years. The successional patterns in vegetation, seed bank, species diversity and plant growth were predicted from tar-pile disturbances with different ages and tar content. The success of natural plant colonization and the establishment of plant communities on the tar-pile disturbances depend upon: (1) age of the tar-pile disturbances, (2) tar content of the piles and soil physicochemical properties, (3) soil moisture content, (4) structure of plant communities in the surrounding landscape, (5) size of the disposal sites and the method of dumping, and (6) prevailing environmental conditions. A management and restoration framework is proposed to optimize the natural recolonization of tar-piles. To retain these ecosystems in a self-sustaining state, some native plant species might be used including: *Aeloropus lagopoides, Aizoon canariense, Anabasis setifera, Fagonia indica, Mesembryanthemum nodiflorum, Reichardia tingitana, Salsola imbricata, Suaeda aegyptiaca, Senecio glaucus, Sporobolus arabicus, Zygophyllum quatarense*, and *Zygophyllum simplex*. To clarify the biological and chemical aspects of the problem, further research on the chemistry of tar-polluted soil and its vegetation in relation to the food web is needed.

Keywords: tar disturbances, vegetation, seed bank, plant growth, succession, bioremediation, arid lands

Introduction

The Gulf region has been subject to increasing environmental impacts from war-related and other developmental activities. Perhaps the most destructive was the Gulf War in 1990, which refocused attention on the problem of terrestrial and marine crude oil spillages and pollution. Much of the spilled oil was deposited either on the coastline or as lakes in confined land areas. As a result, these ecosystems were seriously damaged. Because of the high ambient temperature, oils deposited along these coasts or inland evaporate, leaving a semi-solid tar in the form of an asphaltic pavement. Evaporation is important in the dissipation of relatively light and volatile hydrocarbon fractions and typically accounts for 30–50% of the loss of spilled crude oil in the arid regions (Anon. 1979). In order to clean up the coastline, the deposited tar was stripped off and dumped in the nearby coastal marshes. This method of dumping has an aesthetic difficulty because the tar that is dumped takes a long time to decompose. The piles of tar are progressively increasing in size and presently form a confluent pile landscape.

Despite the recent origin of tar-piles in the coastal marshes of the Gulf region, as well as the lack of physical isolation from the surrounding landscape, the accumulated tar-pile disturbances have developed distinctive plant communities (Hegazy 1995). There is the potential to use local flowering plants in restoration (bioremediation) of these disturbed man-made ecosystems, especially if plant succession were to proceed at a faster rate. Plant succession in the arid deserts of the Gulf is limited by the habitat type, moisture, temperature and the slow turnover of the microbial flora (Goodall *et al.* 1981). Succession can be defined as a repeatable change in community composition through time following disturbance (Drury & Nisbet 1973; Connell & Slatyer 1977; Inouye *et al.* 1987; Pickett *et al.* 1987), but in oil-producing countries, the precise nature of plant succession on man-made tar wastes has not been well documented.

In a previous publication, Hegazy (1995) pointed out that knowledge of plant succession is considered a prerequisite to restoration of disturbed and degraded ecosystems. For tar-polluted coasts, information on plant succession may provide the knowledge which explains the rate and mechanism by which the vegetation structure is altered; an important asset when directing plant succession to meet the objectives of management and restoration of disturbed ecosystems (Grubb 1977; Crawley 1993).

Plant succession is used here as a tool to describe the sequence of flowering plant colonization and development of

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plant communities on a man-made substrate formed of tar mixed with coastal sediments and sea-borne materials. The soil constituents of the piles may contain some biota, including dormant propagules of some coastal plants. It has been argued that succession on man-made wastes is dependent on the origin of the waste (Tilman 1988; Marrs & Bradshaw 1993). It is not in the scope of this study to argue the type of plant succession, but to monitor the changes of vegetation on the tar-piles of different ages. For this purpose, tar-pile wastes are considered a part of the same ecosystem and thus, succession proceeds on a freshly-created waste matrix creating a state of equilibrium with the surrounding environment.

This study consists of an ecological investigation of the tar-pile colonization of flowering plants, in a chronosequence ranging in age from 2 to 14 years depending on the incident of disturbance. The objectives are to document the successional patterns in vegetation, soil moisture, seed bank and plant growth. Management considerations and the restoration framework are presented for future restoration of tar-polluted ecosystems.

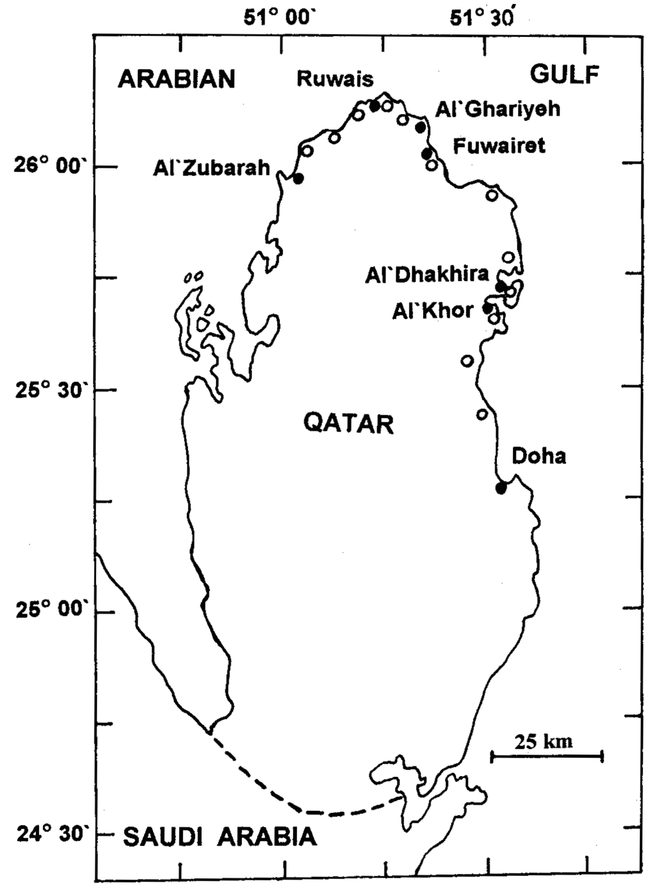

Figure 1 Distribution map of the investigated tar-pile disturbances (o) on the Qatari coastal marshes.

Methods

Study area

The study area extends from north of Al-Zubarah through Ruwais along the northwestern coast to Doha along the northeastern coast of Qatar (Fig. 1). The coastal landscape and soil properties are described in Cavelier (1970) and Hegazy (1995). Soils in both tar-piles and their surrounds contain both fine and coarse sands. Silt and clay fractions are relatively low (<10%). Soils are slightly alkaline, and total soluble salt concentrations range between 600 and 3150 $\mu g\ g^{-1}$.

Tar-piles

The deposited semi-solid tar was stripped off the coastline and dumped in the coastal marshes in dome-shaped confluent piles. The average height of the piles ranges between 1–2 m with a base circumference of about 10 m. During stripping the tar is usually mixed with the coastal sediments. The tar content of piles varies between 10 and 90% (v/v). In this study piles were categorized into four classes based on their tar content: <25%, 25–50%, 50–75% and >75%. The age of piles was ascertained from the date of cleaning and disposal of tar in the coastal marshes (Hegazy 1995).

Soil moisture

For the determination of soil moisture, five replicate samples were collected monthly at a depth of 20 cm from five different tar-piles per category and from their surrounding landscape. Fresh weight of the soil samples was determined, the samples were air-dried to constant weights and were reweighed. Soil moisture content was expressed on an air-dry basis (Allen *et al*. 1974).

Plant colonization

The colonizing efficiency ratio (CER) was calculated for every plant species by dividing the seedling relative density by the mean adult relative cover (Wood & del Moral 1987). This ratio identifies the species that establish effectively. A ratio $\geqslant$1.0 indicates that the species colonized to a greater degree than the species attaining ratios less than unity. Seedling numbers were counted for a 1-m^2 area per site. Plant cover was determined by the line-intercept method (Mueller-Dombois & Ellenberg 1974). Five 5 m tapes were laid out across each tar-pile or selected area of the surrounding landscape. The species intercepting each line were recorded by their number and plant size characteristics. The total plant cover was given by the formula:

$$\text{Cover} = [(\text{transect length-bare ground})/(\text{transect length})]\ 100$$

Species diversity

The Shannon-Wiener index (H`) was applied in both vegetation and seed bank studies to determine whether there

Table 1 Monthly variations in the soil moisture (% air dry weight) on surrounding land and in piles of varying tar content. Figures in horizontal rows with different letters are significantly different ($p < 0.05$, $n = 5$). SL = surrounding landscape.

		Percentage tar content:			
Month	*SL*	*<25%*	*25–50%*	*50–75%*	*>75%*
January	6.1 a	7.1 a	10.5 b	12.8 b	13.2 b
February	7.3 a	9.7 a	10.8 ab	13.6 b	15.4 b
March	5.7 a	6.5 a	8.4 ab	10.5 b	11.9 b
April	5.2 a	6.2 a	7.8 ab	10.1 b	11.5 bc
May	4.1 a	5.4 a	6.9 ab	9.2 bc	10.4 bc
June	3.3 a	5.1 b	6.5 b	8.4 c	9.1 c
July	2.4 a	4.2 b	5.2 b	6.5 bc	8.3 c
August	2.1 a	4.1 b	4.8 b	5.3 b	7.5 c
September	1.8 a	3.5 b	4.1 b	4.7 bc	6.2 c
October	2.0 a	3.2 b	3.8 b	4.5 bc	5.7 c
November	3.4 a	5.5 ab	6.3 b	6.9 b	7.1 b
December	5.3 a	6.8 a	7.9 ab	9.8 b	10.6 bc
Mean	4.1 a	5.6 b	6.9 bc	8.5 c	9.7 c

were any variations in species diversity in the tar-piles of different ages and tar content (Kent & Coker 1992). The index was calculated from the formula:

Species diversity

The Shannon-Wiener index (*H*`) was applied in both vegetation and seed bank studies to determine whether there were any variations in species diversity in the tar-piles of different ages and tar content (Kent & Coker 1992). The index was calculated from the formula:

$$H` = -\sum_{i=1}^{s} Pi \ln Pi$$

where s = number of species, and Pi = proportion of individuals per species in the community made up of s species with proportions $P_1, P_2, P_3, \ldots Ps$. The Shannon evenness index ($E_1 = H` / \ln s$) was applied to quantify the evenness component of diversity. The value of $E_1$ expresses $H`$ relative to the logarithm of the number of species in the sample.

Seed bank

Soil samples from the tar-piles and their surrounding landscape were collected in September 1993, at the end of the dry period, and following seed dispersal. Five randomly-distributed soil samples from every pile with different tar content and age class were collected and used for the determination of germinable soil seed bank (cf. Hegazy 1996). The experiment was conducted from January to March 1994, in a controlled greenhouse (Faculty of Science, University of Qatar) at a constant air temperature of 25°C (298 K) and in natural day/night light.

Growth

Seeds of all plant species were collected from March to May 1994 from the surrounding plant communities of the tar-piles. Soil, collected from plant's natural habitat shortly before the start of the experiment, was excavated from depths between 5 and 20 cm. The soil was sterilized and 5, 10, 20 and 40% (v/v) semi-solid tar collected from recently-dumped piles was added. Seeds were sown in small pots at 0.5 cm depth and watered twice weekly. The experiment was conducted in the greenhouse at a constant air temperature of 25°C (298 K) and in natural day/night light from November to December 1994. Three replicate pots were used per species per tar treatment. There were no pot-bound plants during the course of the experiment. The plant relative growth rate (RGR) was estimated over a five-week time interval as follows:

$$RGR = (\ln W_2 - \ln W_1) / (T_2 - T_1)$$

where W = plant dry weight, and T = time in days on either the first (T_1) or second (T_2) harvest.

Differences amongst tar-piles were tested statistically by ANOVA (Snedecor & Cochran 1967). Plant species nomenclature followed Boulos (1995).

Results

Soil moisture

The soil moisture during the winter rainy season was significantly higher than that of the dry summer months. During the dry summer months, tar-piles retained a higher soil moisture than the surrounding landscape (Table 1). The mean monthly moisture content of soils surrounding piles was 4.1%. Mean soil moisture content of the tar-piles increased with increase in tar content: it was 5.6 in piles with a tar content of <25% and 9.7% in piles with a tar content >75.

Plant colonization

The coastal landscape surrounding tar-piles had a low species complement, with 40 species of flowering plants recorded within a radius of 1 km from the tar-dumping sites. About

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Table 2 Colonizing efficiency ratio (CER) of the different plant species on the 12-year-old tar-piles, with tar content <25%, 25–50%, 50–75%, and >75%. Figures in horizontal rows with different letters are significantly different ($p < 0.05$, $n = 5$). − = species not recorded.

Species	Colonizing efficiency ratio on piles of tar content: <25%	25–50%	50–75%	>75%
Aeloropus lagopoides	0.21 a	0.00 b	–	–
Aizoon canariense	1.70 a	0.60 b	0.83 c	–
Anabasis setifera	0.62 a	0.43 b	0.64 a	–
Atriplex leucoclada	–	0.10	–	–
Cressa cretica	0.52	–	–	–
Cyperus conglomeratus	0.24 a	0.30 a	0.00 b	–
Fagonia indica	1.33 a	0.89 b	0.60 c	–
Frankenia pulverulenta	1.10 a	0.86 b	–	–
Herniaria hemistemon	–	–	0.78 a	0.00 b
Launaea nudicaulis	1.10	–	–	–
Launaea procumbens	0.29 a	0.43 a	0.00 b	–
Limonium axillare	–	–	0.16 a	0.00 b
Mesembryanthemum nodiflorum	0.87 a	1.59 b	1.07 a	2.30 c
Oligomeris linifolia	0.60	–	–	–
Reichardia tingitana	1.05	–	–	–
Salsola imbricata	1.21 a	1.26 a	1.17 a	1.13 a
Suaeda aegyptiaca	1.13 a	1.84 b	1.86 b	1.09 a
Senecio glaucus	0.50 a	0.46 a	0.24 b	2.26 c
Sporobolus arabicus	0.52 a	0.44 a	0.56 a	–
Zygophyllum quatarense	1.42 a	1.38 a	1.05 b	1.26 a
Zygophyllum simplex	0.55 a	1.29 b	1.67 c	–

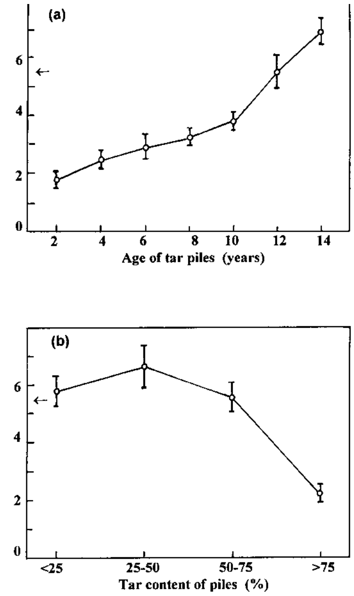

Figure 2 Variations in the plant cover of plant communities on tar-pile disturbances of (*a*) different ages and (*b*) different tar contents. Horizontal arrows indicate values found for the plant communities in the surrounding landscape. Vertical bars indicate the standard deviations.

half of these recorded species colonized and became established on the tar-piles (Table 2). Three species, namely *Salsola imbricata, Suaeda aegyptiaca* and *Zygophyllum quatarense* had a colonizing efficiency ratio (CER) greater than unity, indicating their effective colonization of tar-piles of different tar content. *Mesembryanthemum nodiflorum* and *Senecio glaucus* had the greatest CER (>2.0) on piles of >75% tar content, but their CERs were <1.0 on the piles of lower tar content. This suggests that these latter two species colonize more effectively on piles with a high tar content. The opposite was found for *Fagonia indica* which attained a better CER on piles with <25% tar content. Five species, namely *Oligomeris linifolia, Reichardia tingitana, Aizoon canariense, Cressa cretica* and *Launaea nudicaulis,* were apparently good colonizers on piles with a tar content >25%. The remaining species (Table 2) appeared to have an intermediate CER value, suggesting that their colonization continues at specific microsites. The results suggest that some widespread species may be relatively inefficient colonizers, while some other less-common species may be particularly efficient colonizers of the tar-piles.

Plant cover

Plant cover of tar-piles increased with an increase in age from 1.8% in the two-year-old piles to 6.9% in the 14-year-old piles (Fig. 2*a*). Plant cover in the surrounding communities was 5.4%, indicating that within 12 years, the plant cover on some tar-piles may exceed that of the surrounding landscape. An increase in the tar content of the piles up to 50% resulted in a slight increase in plant cover from 5.8% to 6.3% (Fig. 2*b*), but for piles with a tar content of >75% plant cover was lower (2.2%).

Species diversity

The species richness in the standing vegetation, including perennials and annuals, of tar-piles of different ages (2 to 14 years) ranged from six to 15 species. The species richness decreased with an increase in the pile tar content and ranged between seven and 17 species. For the germinable soil seed bank, the species richness ranged between eight and 19 species for piles of different ages, and seven to 20 species when the tar content of piles was considered. The species

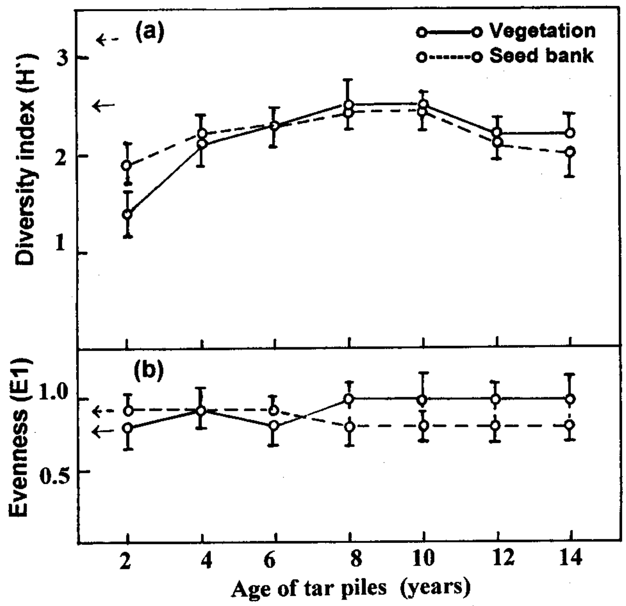

Figure 3 (*a*) Plant species diversity and (*b*) evenness of distribution in the standing vegetation and seed bank on the tar-pile disturbances of different ages. Horizontal arrows indicate the values found for plant communities in the surrounding landscape. Vertical bars indicate the standard deviations.

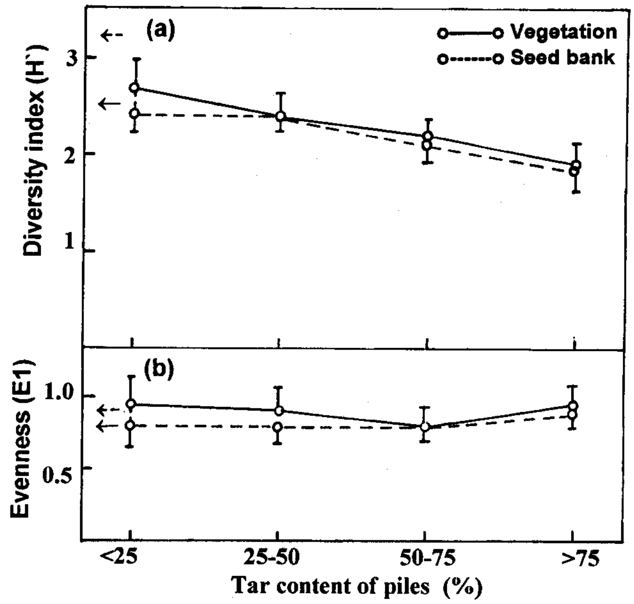

Figure 4 (*a*) Plant species diversity and (*b*) evenness of distribution in the standing vegetation and seed bank on the tar-pile disturbances with different tar contents. Horizontal arrows indicate the values found for plant communities in the surrounding landscape. Vertical bars indicate the standard deviations.

richness increased with age and decreased with increased tar content of the piles. About 26 species were recorded in the seed bank of the surrounding coastal plant communities.

The Shannon-Wiener diversity index (*H*`) indicated that diversity in the standing vegetation and seed bank of the tar-piles increased with age (Fig. 3*a*). *H*` increased from 1.4 to 2.5 in eight-year-old piles in the standing vegetation, and from 1.9 to 2.4 in the seed bank. The species diversity indicated that the established vegetation on the tar-piles attained *H*` values similar to that in the surrounding landscape within 10 years. When the tar content of the piles is considered (Fig. 4*a*), the *H*` values for the standing vegetation decreased from 2.7 on piles with <25% tar to 1.9 on piles with >75% tar, while for the seed bank, the *H*` value decreased from 2.4 to 1.8, respectively. The *H*` values for the surrounding landscape were 2.5 in the vegetation and 3.2 in the seed bank.

The evenness index (E_1) values were notably high in both standing vegetation and seed bank (Figs. 3*b* and 4*b*). The overall E_1 values were 0.77–0.97 in the vegetation and 0.80–0.89 in the seed bank, representing a situation in which all tar-pile colonizing species had equal chances of colonization and distribution on the tar-piles. The high E_1 values indicate the fast natural recovery of tar-piles and their assimilation into the natural landscape.

Growth

Two groups of plants were identified on the basis of their relative growth rate (RGR) on soils of different tar contents (Table 3). The first group showed a positive response with an increase in tar content. The tar-positive group included nine species namely, *Aizoon canariense, Anabasis setifera, Atriplex leucoclada, Fagonia indica, Salsola imbricata, Senecio glaucus, Sporobolus arabicus, Suaeda aegyptiaca and Zygophyllum quatarense,* which attained an optimal RGR with an increase in tar content of the soil. The optimal values of RGR for tar-positive species were reached at a 10%–20% tar content of soils. For the remaining 12 species (Table 3), the increase in the tar content of the soil led to a significant decrease in the RGR of the plants. These species are expected to be sensitive to tar pollution, i.e. tar-negative species. Generally, species with optimal growth rate are characterized by higher RGR values than the sensitive species.

Discussion

Succession occurred on tar-pile disturbances in the Gulf region and produced plant communities similar to those in the surrounding landscape. The study revealed that in the course of plant succession, frequent changes in the dominant species took place, and species colonization and diversity fluctuated, approaching a steady-state within 10 to 15 years. The absence of other comparable studies suggests the process of plant succession on tar-piles in arid regions is unique and varies from normal terrestrial plant succession (Miles & Walton 1993).

Species diversity increased with tar-pile age up to 10 years and decreased with an increased tar content, indicating that diversity attains the highest values in the intermediate successional stage of tar-piles (Shafi & Yarranton 1973; Horn 1974). The difference in diversities between seed bank and vegetation decreased with age and with an increase in tar content. This suggests that (1) there is a continuous and fast

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Table 3. The mean (n = 3) relative growth rate (RGR; mg g^{-1} d^{-1}) of the plant species colonizing the tar-piles with different tar contents in the soil (greenhouse experiment). * = species showed positive response with respect to tar addition.

	Mean RGR (± SD) on tar content of:				
Species	*0%*	*5%*	*10%*	*20%*	*40%*
Aeloropus lagopoides	21 (4)	26 (8)	17 (4)	8 (2)	0
*Aizoon canariense**	33 (6)	45 (8)	52 (10)	31 (5)	9 (2)
*Anabasis setifera**	39 (7)	44 (11)	58 (10)	41 (8)	20 (5)
*Atriplex leucoclada**	36 (10)	42 (7)	51 (9)	29 (7)	12 (3)
Cressa cretica	12 (2)	10 (2)	8 (1)	0	0
Cyperus conglomeratus	17 (4)	15 (3)	11 (2)	8 (2)	5 (2)
*Fagonia indica**	34 (5)	66 (15)	79 (18)	25 (7)	21 (3)
Frankenia pulverulenta	22 (5)	26 (5)	11 (2)	3 (1)	0
Herniaria hemistemon	20 (3)	20 (5)	15 (3)	3 (1)	0
Launaea nudicaulis	17 (3)	15 (3)	5 (1)	0	0
Launaea procumbens	24 (8)	21 (4)	18 (3)	0	0
Limonium axillare	9 (2)	14 (3)	10 (2)	6 (2)	0
Mesembryanthemum nodiflorum	18 (3)	33 (7)	21 (4)	8 (2)	5 (2)
Oligomeris linifolia	11 (3)	5 (2)	3 (1)	0	0
Reichardia tingitana	28 (6)	45 (9)	42 (9)	31 (8)	12 (3)
*Salsola imbricata**	53 (11)	71 (13)	92 (21)	98 (15)	31 (9)
*Suaeda aegyptiaca**	41 (9)	58 (10)	62 (15)	40 (10)	28 (6)
*Senecio glaucus**	34 (7)	49 (11)	78 (16)	82 (11)	15 (5)
*Sporobolus arabicus**	27 (3)	36 (9)	48 (9)	30 (6)	11 (4)
*Zygophyllum quatarense**	46 (8)	65 (15)	74 (17)	83 (12)	23 (4)
Zygophyllum simplex	30 (6)	38 (11)	35 (6)	21 (6)	15 (3)

species replacement and change on the tar-piles, and (2) the early successional species are not often displaced from older piles, perhaps because of localized patches of soil in piles and the relatively stable and even distribution of plant species on the older piles.

As the first plant colonizers progressively grow, their roots grow and rhizosphere microbiota loosen the agglomerated tar masses within the piles and promote mixing with sands (Marrs & Bradshaw 1993). The colonized interstices of the pile disturbances then serve as potential sources of plant colonizers for the non-colonized sites of the piles where succession proceeds. The first colonists can create safe sites *sensu* Harper (1977) that enhance seed germination and survival of their own or other species, resulting in accelerated succession (facilitation *sensu* Connell & Slatyer 1977; Noble & Slatyer 1980), a phenomenon confirmed by increased species richness and diversity and plant growth with the age of tar-piles in the present study. The physico-chemical characteristics of soil change, following contamination by oils or gases, can be directly related to soil microbial activity (Kator & Herwig 1977). In temperate regions, over 100 species of bacteria, yeasts and moulds are known to attack hydrocarbons (Adams & Ellis 1960; Ellis & Adams 1961; Johnson & Frederick 1971). Microbial by-products may change soil moisture retention and release, thereby changing the moisture available to plants, and nutrient release may stimulate plant growth (Ellis & Adams 1961). Mixtures of tar and sand hold more soil moisture than sand alone, as water retention reaches up to five times more than the surrounding landscape. The presence of tar in piles minimizes water evaporation from its sandy component and increases the water-retention capacity of sand pockets and interstices in piles.

The increased plant cover and the relative growth rate of some species in the present study supported these findings. Kator and Herwig (1977) and Hershner and Lake (1980) pointed out that increased activity of microorganisms in the rhizosphere of plant colonizers is extremely important in accelerating tar decomposition and in using oil as an energy source to destroy the most phytotoxic compounds of the tar. It is plausible to assume that tar-pile vegetation and seed bank could have become wind-borne, where dispersal units lodge in the interpile spaces and the sandy interstices of the individual piles. These microsites within the tar-piles are improved by wind-blown sand. Accordingly, soil conditions of confluent piles are evidently suitable for the colonization of an increased number of plant species, which may play a major role in mediating soil changes and plant succession.

It is not uncommon for the growth of some plant colonizers of tar-piles to be stimulated by an increase in tar content. Many other studies demonstrate that oil pollution is not always entirely detrimental to the flowering plants (Cowell 1969; Baker 1970, 1973, 1979; Hershner & Lake 1980; Hegazy 1995). The increased supply of nitrogen and the available soil moisture are possible explanations, but other factors may be involved. Two reasons for the lush growth of some plants in response to oil pollution are that some oils contain compounds related to auxins and gibberellins; in addition some bacteria are capable of using hydrocarbon substrates and fixing atmospheric nitrogen (Baker 1979), as well as nutrients which are liberated from the oil decomposition.

The improved ability of the soil to retain water as a result of the presence of tar is important for supporting lush vegetation on the tar-pile disturbances. Sensitive species which had reduced growth in response to the increased tar content of soils seem to be affected by hydrocarbon toxicity, as well as accumulation of reduced forms of iron, aluminium and other metals in concentrations injurious to plants; this is a well-known phenomenon (Baker 1970; Hegazy 1995).

There are two main successional phases. First, the early successional species phase, where initial colonization is stochastic (random) and depends strongly on the surrounding plant communities. These early successional species belonged to both '*r*-selected' (annuals) and '*K*-selected' (perennials) strategies, e.g., *Salsola imbricata, Suaeda aegyptiaca, Reichardia tingitana, Zygophyllum quatarense, Aeloropus lagopoides, Anabasis setifera* and *Fagonia indica.* Despite their availability in the surrounding plant communities, nitrogen-fixing species were not the principal colonists. This indicates that nitrogen accumulation in tar-piles seems to be derived mainly from tar degradation. Secondly, there is the late successional species phase, where vegetation on the tar-piles approaches that of the surrounding landscape. Most of the late successional species belonged to a '*K*-selected' strategy, e.g. *Zygophyllum quatarense, Anabasis setifera, Atriplex leucoclada, Sporobolus arabicus* and *Herniaria hemistemon*. Many of the tar-pile sites reached the late successional stage within 10 to 15 years. This is attributed to the improved physico-chemical properties of the soil and the rapid growth of the late successional species (Tilman 1985), and the release of mineral nutrients from the decomposition of tar in the soil.

Complete recovery of tar-piles and their assimilation into the undisturbed landscape is possible. The continued dominance of some species in different successional stages is likely because of their superior ability to excel in disturbed areas. The earlier successional species of tar-piles, such as *Salsola imbricata, Suaeda aegyptiaca* and *Zygophyllum quatarense*, had a higher colonizing efficiency and better growth rate than the later successional species (Table 2). The results demonstrate that for fast and successful flowering plant restoration of tar-piles, the ecosystem must be in harmony with the natural tendencies in the surrounding landscape. The knowledge of the adaptive features of colonizing plant species helps to align the plant capabilities with site-specific microenvironmental characteristics. Long-term interactions amongst the successional species, pollutant cycling and environmental conditions in tar-pile disturbances need further investigation.

Management and restoration framework

The main goal of most restoration programmes of tar-polluted lands is to create environmentally-acceptable and self-sustaining ecosystems as quickly as possible (Hegazy 1995). Of the vascular plant species constituting the flora of tar-pile disturbances, about 25% are active and effective colonizers (Table 2). Plant colonization provides a visual display of tolerant species and adapted ecotypes from which plant species and materials should be properly selected for restoration. Care must be taken in selecting the species, together with combinations of tar-pile soil content, that are compatible with succession, and which, in turn, accelerate its development.

Restoration of tar-polluted lands may be carried out in the context of naturally- or artificially-accelerated plant succession. The driving force is the activation of plant species establishment by a stimulus or stimuli. Establishment of particular species may be a response to a single stimulus, or to a combination of stimuli of which soil moisture, percentage of tar in piles, microbial inoculation and seeding of flowering plants are the most obvious. Once a population or community has been initiated, the assemblage of species often remains static, being similar to plant communities in the surrounding landscape.

In order to put forward a restoration framework, the policy of 'laissez-faire' is acceptable but slow, and to restore tar-polluted lands to a better system quickly, intervention and deliberate management are required. The botanical values of the changing plant communities during the course of succession are the improved soil conditions and the fast natural recovery of tar-piles and their assimilation into the surrounding landscape. Here the objectives of tar-pile restoration are directed at increasing the diversity of plant communities, rather than maximizing suitable conditions for a few species.

The restoration framework illustrated in Fig. 5 relates specifically to the coastal habitats of the Gulf region, which are characterized by relatively low species diversity. This framework may be readily modified to accommodate more complex interactions and pathways which occur in other arid-land habitats. The framework should start with the survey and evaluation of the coastal marshes. It is essential to survey and evaluate the marshes at the five different levels, i.e., biological, physical, social, economic and environmental. Location of environmentally-compatible disposal sites in the natural habitats of the coastal marshes comes next. It is proposed here that tar disposal be carried out on small sites in staggered settings, which might be referred to as patchwise tar dumping. The surrounding plant communities provide a good seed or vegetative propagule supply for tar-pile invasion. A system may be provided so that selected sites are managed in a co-ordinated manner to fulfil the clean-up operations of tar at local or regional levels.

Tar disposal sites should be explored and established, taking into consideration their topography, water table, drainage and biological diversity. Decisions to use landfill or surface disposal for either random or systematic methods of dumping must be effective. Natural plant colonization of tar-piles and the artificial seeding of plant species need to be applied on an experimental basis. To save artificial water application, a single species or a mixture of native species should always be seeded during the rainy season. Native species should be selected from populations of the most active tar-pile colonizers (Table 3). Typically, a series of pile treatments (stimuli), such as addition of ameliorants or fertil-

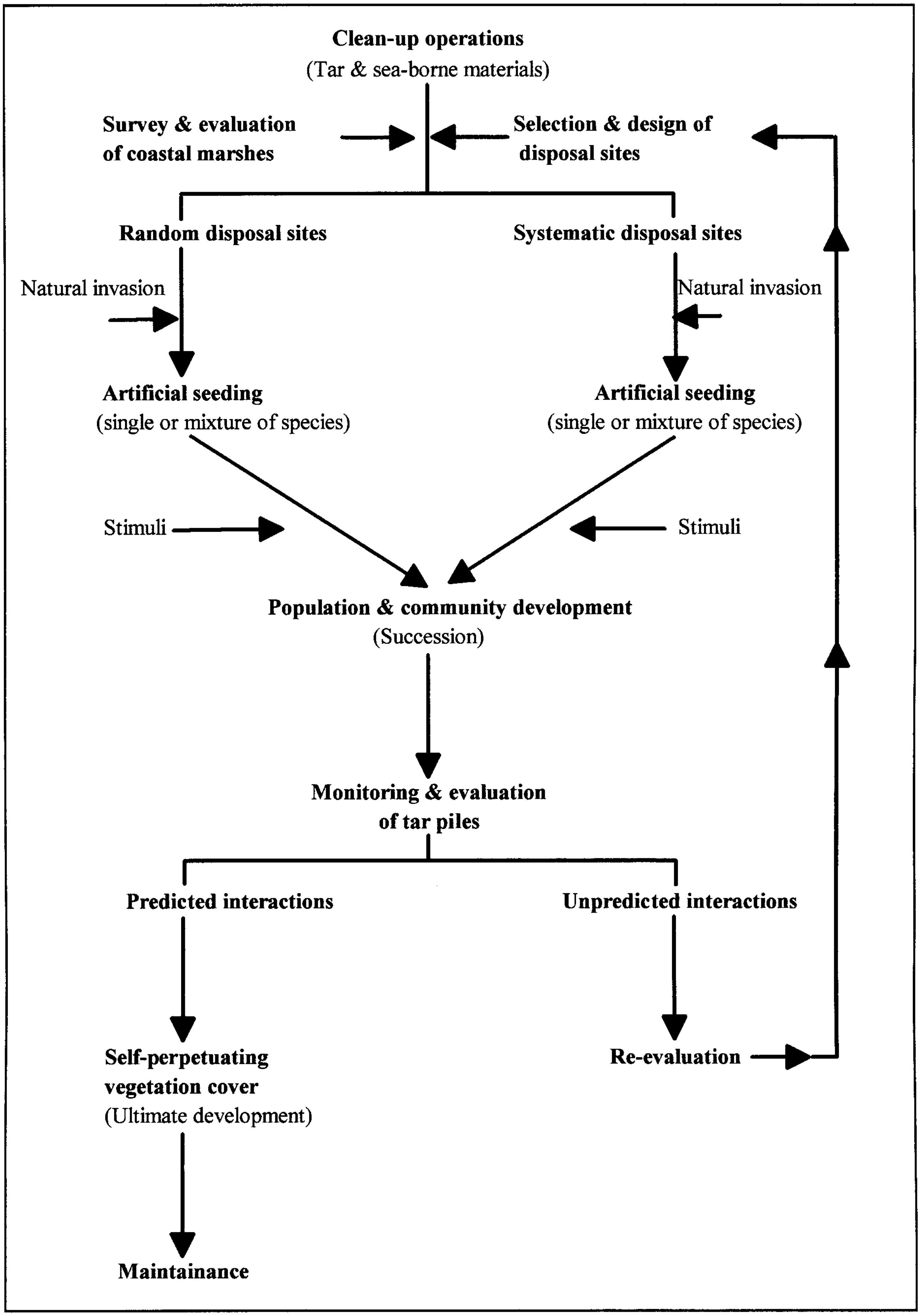

Figure 5 Flowering plant restoration (bioremediation) framework for tar-pile management.

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izers, microbial inoculation and watering techniques (Bradshaw & Chadwick 1980), may then be tested and the effect on population and community development (succession) determined (Fig. 5). Information gained from monitoring plant succession on tar-pile disturbances may help to predict interactions needed to decide about ultimate development of a self-perpetuating vegetation (Fig. 5).

The role of flowering plant succession in restoration of tar-polluted coasts is better understood through coordinated research programmes which address a wide range of successional events as a result of various disturbances and plant-plant interactions (Bazzaz 1990). One of the most obvious ways is to control plant succession on man-made tar-piles by managing the stochasticity (randomness) from the initial colonizing phase by supplying the seeds of appropriate local species (Marrs & Bradshaw 1993; Hegazy 1995). Restoration strategy must consider an accelerated tar decomposition and release of the essential minerals. The addition or encouragement of soil animals promotes this process.

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