Cost and effect of native vegetation change on aeolian sand, dust, microclimate and sustainable energy in Kuwait

Ali Al-Dousari a, Ashraf Ramadan a, Ayman Al-Qattan b, Sara Al-Ateeqi c, Hassan Dashti d, Modi Ahmed e, Noor Al-Dousari a, Noof Al-Hashash a and Ahmed Othman a

aEnvironment and Life Sciences Research Center, Kuwait Institute for Scientific Research; bEnergy Research Center, Kuwait Institute for Scientific Research; cNEST Research Group, EcoLife Sciences Research and Consultation, Kuwait; dDirectorate General of Civil Aviation, Kuwait; ePublic Authority of Agricultural and Fish Resources (PAAFR), Kuwait

ABSTRACT
This study deals with the vegetation change in Kuwait from 1974 compared to recent vegetation map and their capabilities on trapping mobile sand, dust and carbon dioxide (CO2). The average cost of one cubic meter removal of encroached sand around infrastructures in Kuwait is 1.32 USD. The capability of trapping sand is much higher for Haloxylon sp. than Stipagrostis sp. by 100%. The areas that were covered by Haloxylon in 1974 lose recently 4385 km² for the benefits of Stipagrostis causing the formation of a new mobile sand corridor. The total estimated annual cost for the vegetation change is 35,429,379 USD obtained from the costs of sand encroachment, CO2 consumption loss and solar energy efficiency loss. Rehabilitation for areas that were occupied with large size canopy vegetation will surely cause a decrease in the aeolian activities and air temperature, lower the albedo and increase the precipitation and solar energy production.

1. Introduction
Arid and semi-arid areas suffer from the consequences of wind erosion [1,2]. As fine sand and silt particles are very sensitive to wind erosion [3]. Several studies have demonstrated that vegetation is positively correlated with wind erosion [19,20,21]. Density in order to prevent turbulence increase, which shows that attention should be given to the vegetation protection of the soil surface in desert areas, a combination of native shrubs and trees is ideal. Understanding the effectiveness of native plants in reducing aeolian sediment transport is essential when considering the re-vegetation of degraded land [16,17,18]. Other studies show that attention should be given to the vegetation density in order to prevent turbulence increase, which is positively correlated with wind erosion [19,20,21].

The desert ecosystem in Kuwait is almost 14,240 km² representing virtually 80% of the country [20].
The desert ecosystem in Kuwait is fragile, susceptible to widespread deterioration and exhibiting low biomass production resulted from both anthropogenic and natural factors including vegetation change [22]. This causes the loss of most of the vegetative cover and extension of bare ground in the desert [23]. Land degradation represented by vegetation degradation and the loss of fauna and flora biodiversity is of great concern on the desert ecosystem in Kuwait as it has a damaging effect on natural resources. Kuwait is planning to put a National Biodiversity Strategy (NBS) to maintain land health, ecological systems and preserve biological diversity [24].

Several wind tunnel trials concluded that vegetation reduces the total aeolian sediment transport with the transport rates depending on the vegetation porosity and density [25]. Burri et al. [17] showed a mass flux exponential decrease with an increase in native vegetation cover, although with low vegetation cover (around 3%) an increase in the mass flux was observed. As far as “nabkhas” are concerned, Li et al. [26] observed that vegetation had the following effect: a) reduction of airflow above the sand mounds around the plant “nabkhas”, b) change of the wind profile upwind and downwind of the nabkha, and c) reduction of the aeolian transport from the nabkh area. However, studies done so far for understanding the effects of vegetation on change of micro-climate (temperature, wind and rain), mobile sand and dust accumulation rates, wind energy, and economy are insufficient. Therefore, to understand the effect of vegetation, the effect of the change in vegetation spatially and temporally should be taken into consideration.

The morphology of encroached sand around native vegetation in northern Kuwait was first studied by Khalaf et al. [27]. In the last two decades, more consideration has been given to the native vegetation classification and distribution in Kuwait [28]. Emphasis on preparing Kuwait vegetation maps has been made since 1955 [29]. Major changes in plant distribution in Kuwait, particularly Rhanterium epapposum and Haloxylon salicornicum, have been shown to be due to hydro-aeolian processes and human activities [30]. These changes have definitely some environmental and economic consequences. Al-Awadhi and Al-Dousari [31] listed species of dominant perennial plants that played a major part in controlling the mobile sand encroachment problem in Kuwait. There is a strong indication that climate change affects the geographical distribution of dominant perennial plants in Kuwait [20,32,33]. Therefore, this study aims to provide a further understanding of the cost and effect of vegetation change on the mass flux of aeolian sediment (mobile sand and dust) and CO₂ levels and energy production from photovoltaic panels.

2. The study area

Kuwait is characterized by a hot, windy and arid desert environment. The climatic aridity is illustrated by the

![Figure 1.](image-url)
extreme diurnal air temperature variations. The meteorological data for 1958–2017 shows the mean temperature in summer (June - October) to be 37.4°C, while the mean air humidity percentage and evaporation rate are 55.3% and 6,060 mm/yr, respectively. Rainfall can be described as variable and low with 113.8 mm as mean annual (2010–2017). The prevailing wind in Kuwait is northwesterly and northerly representing approximately 60% from the entire wind direction signal [34]. Other wind directions account for shorter durations/less frequency and lower wind speeds (Figure 1a). The average wind speed is 4.8 m·s⁻¹ [35].

In Kuwait, the surface is carved into a depositional sequence locally named the Kuwait Group (Miocene to Pleistocene). The Kuwait Group is sequenced into three main Formations, namely; Ghar, Fars and Dibdiba [36]. At the northern part of Kuwait, a Pliocene–Pleistocene sand and gravel deposits form as ancient delta deposits called the Dibdiba Formation (Figure 1b), while in the southeast Miocene sand, clay and nodular limestones of the Fars and the Ghar Formations outcrop [37]. Most of the wadis and hydrological depressions are located in the northern part of Kuwait within the Dibdiba Formation outcrop as it represents an ancient delta deposit. During the 1970s, native plants, which are efficient in controlling mobile sand and dust, were present within the wadis and hydrological depressions. More recently, the vegetation map of Kuwait has shown these plants to be replaced by other native plants which are less efficient in controlling mobile sand and dust.

3. Methods

This study passes on the following main stages:

The first step was to collect and analyze available data on the volume of encroached sand around the main infrastructures in Kuwait during 2013 and the cost of its removal. The installations considered were: highways and main roads, oil wells and gathering centers, military camps and airbases. This enabled the estimation of the average cost of removal of sand.

The second step covers the changes in dominant perennial plant species from 1974 compared with the latest vegetation map in Kuwait 2007 and their capabilities in trapping sand (Figure 2). There was no much spatial change in vegetation type was noted recently compared to 2007 [39]. These dominant plants shown in both vegetation maps are Haloxylon salicornicum (Figure 3a), Nitraria retusa (Figure 3b), Cyperus conglomerates (Figure 3c), Panicum turgidum (Figure 3d), Rhanterium epapposum (Figure 3e), Zygophyllum qatarense, Centropodia forsskalii and Stipa grostis plumosa (Figure 3f). Moreover, in order to evaluate the influence of vegetation change on climate, rainfall and temperature, 14 meteorological stations data were used obtained from the Civil Aviation Meteorological Department (CAMD) and Kuwait National Meteorological Network (KNMN) at Kuwait Institute for Scientific Research (KISR) for two decades, 1971–1980 and 2008–2017 was analyzed. These two decades cover the vegetation map periods. The data of deposited dust was monitored in Kuwait and obtained from the Kuwait Environmental Public Authority (KEPA).

In order to test the efficiency of the mentioned plant species in capturing dust and mobile sand, the morphometric properties (length, width and height) were evaluated using intensive fieldwork in Kuwait (Figure 4a). The largest nabkhas form around each plant species were visually inspected and measured within the 8 vegetation units in the two vegetation maps. As this study focus on plant efficiency in controlling aeolian transport and the resulting accumulations, the top 20 maximum total volume of sand accumulation (i.e. top 20 nabkhas) for the 8 dominant plant species were considered in this study. The average calculated volume of trapped

![Figure 2](image-url). Vegetation maps for Kuwait [40] (a) and [29] (b).
sand around native plants was converted into economic value, i.e. cost saving on the removal of sand, using the results from Al-Dousari et al. [41] (Figure 4b):

\[
\text{The cost saved by single plant} = \left( \frac{\pi \cdot a \cdot b \cdot c}{12} + \frac{\alpha \cdot d^2 \cdot \tan \theta}{5} \right) \times 1 \text{m}^3 \cos \theta \quad (1)
\]

where \( a, b, \) and \( c \) are radii in all three directions, \( a_1 \) is the height from ground level and equal to vertical radii, \( b_1 \) is total width, and \( c_1 \) is horizontal radius, \( \alpha = \frac{d}{\theta} \) and \( \tan \theta = \frac{d}{b_1} \).

Then by measuring the loss of the area or gain for each of the eight plant types in both vegetation maps.

**Vegetation Change**

\[
= \text{Area covered in 2007} - \text{Area covered in 1974} \quad (2)
\]

The estimation of the total number of native plant species is based on the type and average density of vegetation within Kuwait. The number of plants was estimated by the measuring area occupied in both maps taking into consideration 50m average distance. The 50m distance is adopted based on previous studies covering dominant native plants in Kuwait [30,42]. By means of both methodological stages above; the economic value, i.e. the saving cost, for each plant species was estimated.

The third stage is finding the capabilities and cost of vegetation in trapping carbon dioxides (CO₂) from an economic point of view utilizing the Yashiro et al. [43] method which uses average area covered by single plant canopy to derive an estimate of the consumed CO₂ in kg·m². This was performed for the eight types mentioned in the 1974 and 2007 vegetation maps. The estimated mass of consumed CO₂ was converted into kWh using a conversion factor of 0.28307 kg CO₂ for each kWh. Finally using the local price of 0.14 USD per kWh, based on the National Bank of Kuwait [44], an estimate of the total financial impact due to change in vegetation was obtained by adding the three components, i.e. due to trapped sand, consumed CO₂ and cost effect on photovoltaic energy (Figure 5). The equations for obtaining the tree cost components as
follow:

\[ A = a \cdot b \cdot c \]  \hspace{1cm} (3)

\[ B = a \cdot d \]  \hspace{1cm} (4)

\[ C = e \cdot f \cdot g \]  \hspace{1cm} (5)

The estimated total cost for vegetation Change

\[ = A + B + C \]  \hspace{1cm} (6)

Where:

- \( a \): The estimated number of plants loss/gain,
- \( b \): the capability of single vegetation family to trap mobile sand,
- \( c \): 1.32 USD (the cost of one cubic meter of encroached sand in Kuwait),
- \( d \): the estimated mass of consumed CO\(_2\) cost of single vegetation family which is converted into kWh using a conversion factor of 0.28307 kg CO\(_2\) for each kWh. Finally using the local price of 0.14 USD per kWh, based on the National Bank of Kuwait \([44]\),
- \( e \): 4500 megawatts (converted to kWh) from solar energy power units in Kuwait 2030,
- \( f \): 0.14 USD/kWh,
- \( g \): 45% (average loss in efficiency from the expected used PV panels) in accordance with Al-Dousari et al. \([41]\).
4. Results and discussion

4.1. Vegetation change effect on mobile sand and dust

Careful examination of the 8 dominant perennial plant species in Kuwait and their capabilities in trapping mobile sand and dust from an economic point of view; reveals that the *Haloxylon salicornicum* and *Nitraria retusa* species are the most efficient native plants in trapping mobile sand, while *Centropodia forsskalli* and *Stipagrostis plumosa* species are the least efficient ones (Figure 6). An increase in mobile sand intensities and change in the soil characteristics from calcretic sand (suitable for *Haloxylon sp.* and *Rhanterium sp.*), which were the most two dominant native plants, lost areas for the benefit of other low capable plants in controlling mobile sand and dust. The sand trapping capability of *Haloxylon sp.* is 100% more than *Centropodia sp.* and *Stipa-grostis sp.* and 85% more than *Cyperus sp.* Many studies indicate an exponential decrease in particle transport rates when particles move from bare land into vegetated land [45].

In Kuwait, there are two main trajectories of mobile sand these are Huwaimiliyah-Wafra, and Um Niqa-Sabiya (Figure 7). The Huwaimiliyah-Wafra zone is the longest with 160 km length, 20 km average width and 4,224 km² area. The Um Niqa-Sabiya has an area equal to 576 km². The mobile sand transported within these major trajectories is costing Kuwait a lot. The western area of Kuwait is the most highly deteriorated in comparison to other areas. Also, a tremendous change from high to low capability plants in trapping mobile sand has resulted in the formation of a new wind corridor on the western side of Kuwait with a total area of around 2,771 km². The aeolian sand and dust can easily pass through these wind corridors causing sand encroachment which is considered a huge threat to the main infrastructure. The amount of removed encroached sand from different facilities and installations all over Kuwait and the associated cost were collected and analyzed (Table 2). The facilities affected included oil wells, oil gathering centers, air bases, and main highways. The total amount of sand cleaned from the main infrastructures in Kuwait in 2013 was around 3,160,660.52 m³ costing Kuwait around 4,169,766 USD. In reference to later data, the average cost of removal of one cubic meter of encroached sand in Kuwait is 1.32 USD.

Recently, i.e. 2011–2017, the amount of deposited dust has increased 2.78 times compared to 1974–1980 (Figure 8). The deposited dust increased from 109.4 t.km⁻² during 1974–1980 to 392 t.km⁻² during 2011–2017.

### Figure 6. Mean capability for native plants in trapping aeolian sand and dust in Kuwait.

![Graph showing the mean capability for native plants in trapping aeolian sand and dust in Kuwait.](image)

### Table 1. Variations in vegetation type area in Kuwait from 1974 to 2007.

| Vegetation family and dominant plants | 1974 | 2007 | Difference |
|--------------------------------------|------|------|------------|
| Family                               | Area Km² | Area Km² | Area Km² |
| Cyperetum                            | 1659.83 | 4380.89 | 2721.07   |
| Haloxyletum                          | 8202.08 | 3817.34 | -4384.74  |
| Panicetum                            | 82.72  | 85.77  | 3.05      |
| Rhanterietum                         | 5201.96 | 323.18  | -4878.78  |
| Zygophylletum                        | 737.39 | 55.06  | -682.34   |
| Centropodietum                       | 0.00   | 152.89 | 152.89    |
| Stipagrastietum                      | 0.00   | 6336.34 | 6336.34   |
| Halophyletum                         | 0.00   | 410.48 | 410.48    |


Figure 7. The three main corridors of mobile sand placed on the drainage system map for Kuwait (arrows indicate the movement direction of mobile sand).

Table 2. The annual amount and cost for removing encroached sand from main facilities and infrastructures in Kuwait during 2013.

| Settlements         | Total Amount of Sand Removal (m³) | Total Cost of Sand Removal (USD) | Cost for sand removal per m³ (USD) |
|---------------------|----------------------------------|---------------------------------|----------------------------------|
| Oil facilities      | 347,310                          | 993,862                         | 2.862                            |
| Main Highways       | 2,651,431                        | 2,141,757                       | 0.81                             |
| Power stations      | 160,600                          | 953,452                         | 5.95                             |
| Military Bases      | 1,320                            | 78,694                          | 59.62                            |
| Average             | 790,165.13                       | 1,042,441                       | 1.32*                            |
| Total               | 3,160,660.52                     | 4,169,766                       |                                  |

*Calculated by dividing the total cost with total amount of sand removal.

4.2. Vegetation change effect on meteorological parameters

Vegetation modifies surface land properties, mediating the exchange of energy, moisture, trace gases, and aeolian activities [46]. Land surface albedo plays a major rule in land surface climate [47]. The vegetation dynamics are represented by the so-called Normalized Difference Vegetation Index (NDVI), which represents the relative abundance of vegetation in a certain area and related to high and low albedo [48,49]. The relationship between long-term mean rainfall and vegetation cover with mean albedo is proven to be strong and curvilinear [47]. Long-term climate patterns, which control vegetation type and canopy structure, have a greater influence on albedo than short-term fluctuations in rainfall [46]. Impacts of future vegetation change on rainfall are uncertain but could be of similar magnitude to those caused by climate change [47]. The average canopy diameter of the Haloxylon sp. is around 2.5 m while it is around 0.15 m for Centropodia forsskaliai and...

Figure 8. Annual deposited dust in Kuwait comparing between two decades (2011–2017) and 1974–1980.
Stipagrostis plumose. With mentioned 53% reduction in the Haloxylon sp. and no change in the vegetation cover of the other two species (Table 1), this has resulted in an increase in the albedo while the mean rainfall in Kuwait reduced by 42% in the recent decade (2011–2017) compared to 1991–1980 (Figure 9a). On the other hand, the temperature has risen by 1.58 degree centigrade compared to 1991–1980 (Figure 9b). A plant selection chart derived from a temperature prediction models show that plants with larger canopy can cause for a maximum cooling potential and lower albedo compared to smaller ones [50].

4.3. Vegetation change effect on wind and solar energy

The average wind speed distribution map (Figure 10a) and the wind power density (W/m²) at 10m (Figure 10b) and 30m (Figure 10c) height from 14 meteorological stations in Kuwait show higher values to the northwestern as areas as being invaded by low capability native plants mainly Stipagrostis sp. and Centropodia sp., which are known to have very little efficiency in trapping mobile sand. These areas were occupied by Haloxylon salicornicum in 1974 with higher capability in trapping mobile sand reaching up to 9.73 m³. Therefore, the northwestern areas of Kuwait are the most proper areas for establishing wind power station (Figure 10d).

Moreover, the creation of a third wind corridor on the western side of Kuwait poses some challenges to photovoltaic energy generation. These challenges are represented in the formation of thinly crusted mud and/or carbonates coatings at the photovoltaic panel surfaces which is caused by aeolian deposits (dust and sand). When examining the potential feasibility of establishing solar and/or wind energy systems in Kuwait and relying on one year’s operation of wind farms and solar units on the western side of Kuwait, the results confirmed...
that wind energy production exceeded the industry average. Wind energy was associated with high capacity factors throughout the year, resulting in an annual power production that is 2.3 times higher than that of PV cells; powering 450 homes compared to 199 homes for photovoltaic cells. The described vegetation change has resulted in the affected area is more suitable for wind-derived energy as opposed to solar as the solar or photovoltaic cells will lose efficiency due to sand and dust coverage. Low quality flat solar cells (TF4) have displayed a loss of about 77% in efficiency over 11 months while for high quality cylindrical photovoltaic (PV) thin-film cells without tilting (TF3), the corresponding loss in efficiency is about 20%
Table 3. Detailed and total vegetation change cost (USD) in Kuwait.

| Vegetation Family | Estimated number of plants loss/gain | Estimated sand release/gain (m³) | Estimated sand cost for vegetation change | Estimated CO₂ cost for vegetation change | Estimated PV energy loss cost for vegetation change | Estimated Total cost for vegetation change (USD) |
|-------------------|-------------------------------------|---------------------------------|------------------------------------------|------------------------------------------|-------------------------------------------------|-----------------------------------------------|
| Cyperetum         | 1088428                             | 2784486                         | 3675522                                   | 355689                                   | 0.00                                            | 4031212                                      |
| Haloxyletum       | −1753896                            | −25431492                       | −35659569                                 | −4585273                                 | −283,500                                        | −38154842                                    |
| Panicetum         | 1220                                | 6216                            | 8205                                      | 399                                      | 0.00                                            | 82604                                        |
| Rhanterietum      | −1951512                            | −4399619                        | 5807497                                   | −637738                                  | 0.00                                            | 5169759                                      |
| Zygophylletum     | −272936                             | 0.00                            | 0.00                                      | −89193                                   | 0.00                                            | −89193                                       |
| Centropodietum    | 61192                               | 0.00                            | 0.00                                      | 5199                                     | 0.00                                            | 5199                                         |
| Stipagrastietum   | 2534536                             | 0.00                            | 0.00                                      | 215349                                   | 0.00                                            | 215349                                       |
| Halophyllum       | 164192                              | 3595805                         | 4746463                                   | 536566                                   | 0.00                                            | 5283029                                      |
| Sum               | −23444604                           | −30946877                       | −4199002                                  | −283,500                                 | −35429379                                      | −35429379                                    |

(Figure 11). Kuwait is planning to generate around 4500 megawatts from solar energy in 2030 (personal communication, https://phys.org/news/2015-09-kuwait-mn-solar-energy.html). The average loss in efficiency from the expected used PV panels is around 45%; therefore, the expected energy loss mainly due to vegetation change is around 2025 megawatt with 283,500 USD as annual cost taking in consideration the local price of 0.14 USD/kWh in Kuwait based on the National Bank of Kuwait [44].

4.4. Vegetation change effect on CO₂ cost

The estimated mass of consumed CO₂ for total loss or gained plants was converted into kWh using a conversion factor of 0.28307 kg CO₂ for each kWh. Finally, using the local price of 0.14 USD per kWh, based on the National Bank of Kuwait [44]. The total annual cost resulted from CO₂ consumption is (4,199,002 USD).

4.5. Vegetation change total cost

In accordance with the capability of native plant species in controlling mobile activities and the absorbance of carbon dioxide, the total estimated cost resulted from vegetation change in Kuwait is more than 35.4 million USD (Table 3). Most of this estimation cost is from clearance of encroached sand and dust (30,946,877 USD) around main infrastructures and human settlements. The carbon dioxide levels are considered very high in Kuwait [44].

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ORCID
Ali Al-Dousari  http://orcid.org/0000-0002-7621-8386
Ayman Al-Qattan  http://orcid.org/0000-0003-4730-5736
Sara Al-Ateeqi  http://orcid.org/0000-0003-3383-8638
Hassan Dashti  http://orcid.org/0000-0001-8912-0356
Modi Ahmed  http://orcid.org/0000-0002-6626-1276
Noor Al-Dousari  http://orcid.org/0000-0001-9535-3877
Noof Al-Hashash  http://orcid.org/0000-0002-9897-4078
Ahmed Othman  http://orcid.org/0000-0002-4580-7532

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