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Edited by Levente Hufnagel

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Meet the editor

Dr. Levente Hufnagel is an associate professor and senior researcher at Szent István University, Gödöllő, Hungary, in climate change and ecosystem ecology, biogeography, biometrics, and ecological research methodology, with over 20 years of experience at leading Hungarian academic institutions teaching PhD, MSc and BSc students from various social and cultural backgrounds. He has more than 160 scientific publications (in both aquatic and terrestrial ecological aspects of plants, animals and microbes, at community as well as population level) and more than 700 independent citations. As a participant of several big ecological research and development projects, Dr. Hufnagel has significant experience in multidisciplinary cooperations (with more than 180 coauthors in different publications). As the supervisor of several PhD, BSc and MSc theses, and as editor-in-chief of an international scientific journal indexed by Web of Science and Scopus, Dr. Hufnagel has wide supervising and editing experience. He graduated from Eötvös Lorand University with his Masters degree in Ecology and Evolutionary Biology and PhD degree in Hydrobiology, he also graduated from Szent István University with a PhD degree in Agricultural Science.

Contents

Preface

This book, Community and Global Ecology of Deserts, gives an interesting overview of the frontiers of desert ecological research.

Our book consists of five chapters: the first about the global aspects and scientific importance of desert ecological research, the second about a case study in connection with desertification dynamics and ecosystem services, the third about special zoological research about an arthropoda species, the fourth about ecological and environmental assessment of desert wetland complex, and the fifth about a very special plant-ecological impact of sand electrification. Each chapter is unique and interesting.

I am sure that this book will be very useful for everybody – researchers, teachers, students or others interested in the field - who would like to gain insight into modern desert ecological research.

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Chapter 1

Introductory Chapter: Global Aspects and Scientific Importance of Desert Ecological Research

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Melinda Pálinkás and Réka Homoródi

Additional information is available at the end of the chapter

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1. Introduction

If ecologists or environmental scientists are talking about desert ecological research, then almost everyone is thinking about specific desert flora [1–5], fauna [6, 7], or desertification itself as a consequence of climate change [8, 9], or sand dunes-triggered disasters [10]. In fact, the importance of ecological research in deserts is far more general and wider. For deeper understanding of this importance need to overview the definition of deserts from different viewpoints, the real areas of deserts, and some basic production biological data.

2. Definition of deserts, semi-deserts, and habitats prone to desertification

Efficient functioning of the Earth's ecosystems is based on the autotrophic plant life, which can make use of the radiation energy of the Sun directly. This plant life needs, besides the light of the Sun, simultaneous availability of minerals in the lithosphere, carbon dioxide in the atmosphere, and liquid water in the hydrosphere. Thus, biosphere appears on the interface of these three spheres. Where these four factors are available in the most efficiently usable form, tropical rainforests can be found. Every other habitat is more or less a "struggle zone" for plants because some of the four above mentioned factors limit the biosphere. Based on the degree of environmental limitations, ecosystems can be arranged along a scale. Desert ecosystems can be found on the opposite endpoint of this scale compared to tropical rainforests. Semi-deserts can be found near deserts on this imaginary line, just a little bit nearer the other endpoint of the scale.

3. Vegetation approach

If this most general definition of deserts is accepted, several habitats, which are not referred to as deserts in the habitual language use must be considered to be deserts. In order to quantify the scale, we can use biomass per area as a static indicator as well as net primary production per area per time as a dynamic indicator. Biomass of tropical rainforests is characterized by 2200 g/m^2/year net primary production (NPP) and 45,000 g/m^2 biomass, this is currently the "ideal existence status" of the biosphere. In the case of deserts, NPP is between 0 and 3 g/m^2/year and biomass is between 0 and 20 g/m^2. In the case of semi-deserts, NPP amounts to 3–150 g/m^2/year and biomass amount to 20–700 g/m^2.

Desert or semi-desert conditions can be caused by:

1. Lack of liquid water usable for plants (arid areas without precipitation)

- areas without precipitation (orographical, e.g., Gobi, Tibet, or cool, dry deserts, e.g., Namib, Atacama)
- areas with much larger evapotranspiration than precipitation due to the heat (southern and central part of Sahara)
- permanently frozen areas (Greenland, Antarctica, and peaks of high-altitude mountains)
- sheer, unweathered rock surfaces where water runs off (barren, rocky areas in mountains)

2. Lack of access to minerals in the lithosphere

- Photic zone of open oceans (where biomass has a desert value of only 3 g/m^2, which is even less than that in the Sahara, however, NPP has a semi-desert value of 125 g/m^2/year)

3. Lack of light

- Abyssal water of open oceans, caves (special ecosystem with low productivity)

4. Lack of air and light

- Inner part of the rock masses of the Earth (where microbial life may often exist)

5. Continuous physical disturbance, which prevents plants from settling in

- Coastal tidal zone
- Fast-running reaches of rivers
- Shifting sand areas

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- Volcanic areas exposed to regular lava flow or tuff eruption
- Areas exposed to anthropogenic transformation and disturbance (urban concrete surfaces, airports, highways—"anthropogenic deserts")
- Areas exposed to extreme environmental pollution (e.g., mazut lakes)
- Certain agricultural areas with low productivity (not irrigated, plowed areas with regular disturbance, lying fallow most of the year, semi-desert category in annual average)

At the borders of the semi-desert category, there are tundra, open grasslands (e.g., rocky, saline, and mountain) and several other habitat types besides classic tropical and temperate semi-deserts.

4. Climatic approach

Vegetation is normally able to evapotranspirate water equivalent to 20 mm of precipitation at a temperature of 10°C. A month is considered to be climatically arid if its monthly average temperature exceeds double the monthly amount of precipitation. If each of the 12 months of the year is arid in multi-year average, the area is considered to be a desert from a climatic point of view. If less than 2 months of the year are not arid, we speak about semi-desert climate. Similarly, if the multi-year average of the monthly average temperatures is below 0°C for 12 months, we speak about ice desert from a climatic point of view; if the period with an average temperature above 0°C lasts up to 2 months, the climate is tundra. However, the climatic approach may be misleading because the typical vegetation type of a certain area does not depend on the climate only.

Plants and animals have been able to adapt to areas with different environmental (among them climatic) conditions better and better during the evolution (on a historic time scale). In the second part of the Cambrian period (approx. 542–488 million years ago), hot tropical conditions were dominating most of the Earth, however, 100% of land could be considered a desert, only traces of some coastal invertebrates indicate terrestrial life. Also, during the Ordovician (488–443 million years ago), the climate was hot in several areas, the first plants (liver mosses and hyphae) appeared on land, however, this type of vegetation could have reached rather desert than semi-desert level. The first vascular terrestrial plants appeared in the Silurian (443–416 million years ago), however, they began to form vegetation mainly on the waterside, the continents' interior kept being a desert for the most part from a vegetation point of view. During the evolution of terrestrial life, more and more various adaptation modes have appeared in response to the various climatic conditions, and this process is still going on. At the same time, climatic regulation capacity and generally self-regulation capacity, biodiversity, total biomass, and productivity of the biosphere have also shown an increasing tendency (excluding fall-backs caused by climatic variation).

	Therophytes	Cryptophytes	Hemi-cryptophytes	Chamaephytes	Phanerophytes	Epiphytes
Tropical rainforests	—	—	—	10–20%	60–80%	10–20%
Tropical and temperate desert and semi-desert	40–50%	5–10%	10–20%	10–20%	5–10%	—
Ice and tundra	1–5%	1–5%	60–70%	20–30%	—	—

Table 1. Comparison of frequency distribution of plant life-forms (based on [11]).

Vegetation types have reached various levels regarding adaptation to the abiotic conditions of the given habitat, which is also shown by the distribution of plant life-forms. Long-living K-strategists and phanerophyte life-form are dominating where vegetation has been able to adapt efficiently to existing conditions. However, where the habitat is rather a "struggle zone", shorter-living r-strategists, herbaceous annual, or rosette plants are dominant (see **Table 1**).

Thus, deserts and semi-deserts are "front lines" of the expansion of biosphere, and therefore, their research (similarly to tropical rainforests) is highly important regarding life and future of mankind.

5. Importance of deserts and semi-deserts regarding the whole biosphere and human society

Global ecological importance of deserts and semi-deserts in the broader sense can be estimated according to their area and indicators of their vegetation. Tropical rainforest can be a reference base as a counterpoint, however, when speaking about deserts and semi-deserts in the broader sense, tundra and artificial deserts (human-transformed areas) must be considered as well besides tropical and temperate deserts and semi-deserts in the narrower sense. Land takes up approximately 150 million km^2 on Earth from which approximately 15 million km^2 are covered with ice, mainly in Antarctica and Greenland. **Table 2** shows potential and current values of tropical rainforests as well as areas considered as desert and semi-desert in the broader sense, excluding the before mentioned ice fields. **Table 3** shows the sources of data. Comparison of habitat types can be based on carbon stock in the biomass (t/ha), yearly carbon sequestration by primary production (t/ha/year), and biodiversity of the habitat type (species number per 10,000 km^2). These data can be found in **Table 4** and their sources in **Table 5**.

These habitats offer a wide range of ecosystem services, among others due to the climate regulation role of the assimilated and retained carbon stock. Monetary value of these is shown in **Table 6**, based on a price of $11 per ton (Interagency Working Group, 2013).

	Africa km²	South America km²	North America km²	Asia km²	Europe km²	Pacific km²	Total km²
Lowland rainforest	4.0177×10^6–8.7000×10^5	7.0721×10^6–4.5400×10^6	0	3.4907×10^6–1.7700×10^6	0	0	1.4581×10^7–7.8000×10^6
Deserts	1.7022×10^6–1.0932×10^6	2.7405×10^6–8.7276×10^5	2.2211×10^6–5.8855×10^5	1.3390×10^7–6.7763×10^6	0	3.9828×10^6–3.6949×10^6	3.9357×10^7–2.2865×10^7
Tundra	0	0	1.8922×10^6–1.8922×10^6	1.8922×10^6–1.8922×10^6	2.6542×10^5–2.6542×10^5	0	4.0497×10^6–4.0497×10^6
Human areas	1.4140×10^3–4.1679×10^4	7.0490×10^3–1.4854×10^5	2.5700×10^2–1.8185×10^5	$4.3900 \times 10^2 - 3.8400 \times 10^4$	$4.4390 \times 10^3 - 1.1406 \times 10^5$	$4.9000 \times 10^1 - 1.3871 \times 10^4$	$1.3647 \times 10^4 - 5.3840 \times 10^5$

In the case of natural ecosystems, the first number shows the area before human interference, whereas the second one shows the remnant at the turn of the millennium. In the case of human areas, the first value refers to the 1700s, whereas the second one refers to the turn of the millennium.

Table 2. Potential and current areas.

	Africa	Asia	North America	South America	Europe	Pacific
Lowland rainforest	FRA ([12])	FRA ([12])	See at South America	FRA ([12])	—	See at Asia
Deserts	Hannah et al. ([13])	Hannah et al. ([13])	Hannah et al. ([13])	Hannah et al. ([13])	—	Hannah et al. ([13])
Tundra	—	Brink ([14]); Tchebakova et al. ([15]); Golubyatnikov et al. ([16])	Brink ([14]); Tchebakova et al. ([15]); Golubyatnikov et al. ([16])	—	Brink ([14]); Tchebakova et al. ([15]); Golubyatnikov et al. ([16])	—
Human areas	Goldewijk et al. ([17])	Goldewijk et al. ([17])	Goldewijk et al. ([17])	Goldewijk et al. ([17])	Goldewijk et al. ([17])	Goldewijk et al. ([17])

Table 3. Sources of data shown in **Table 2**

	Carbon stock C t/ha	Carbon sequestration C t/ha/year	Species number/10,000 km^2
Lowland rainforest	210	13–17	2750
Deserts	3	1.15–2.69	457
Tundra	2.5	1.94	227
Human areas	5	2.2	1684

Table 4. Carbon stock, carbon sequestration and species number per unit area.

	Carbon stock C t/ha	Carbon sequestration C t/ha/year	Species number
Lowland rainforest	http://www.esd.ornl.gov	Girardin et al. ([18])	Barthlott et al. ([19])
Deserts	Melillo et al. ([20])	Ito and Oikawa ([21])	Ellis et al. ([22])
Tundra	Melillo et al. ([20])	Ito and Oikawa ([21])	Ellis et al. ([22])
Human areas	Melillo et al. ([20])	Haberl et al ([23])	Ellis et al. ([22])

Table 5. Sources of carbon stock, carbon sequestration and species number per unit area values.

	Carbon stock		Assimilated carbon	
	$ on potential area	$ on current area	$ on potential area	$ on current area
Lowland rainforest	1.23×10^{13}	3.76×10^{12}	7.64×10^{11}–9.99×10^{11}	3.76×10^{11}–4.92×10^{11}
Deserts	4.76×10^{11}	2.77×10^{11}	1.83×10^{11}–4.27×10^{11}	1.06×10^{11}–2.48×10^{11}
Tundra	4.08×10^{10}	4.08×10^{10}	3.17×10^{10}	3.17×10^{10}
Alpine vegetation	5.76×10^{10}	2.95×10^{10}	2.41×10^{10}	1.23×10^{10}
Urban area	2.75×10^{8}	1.09×10^{10}	1.21×10^{8}	4.78×10^{9}

Table 6. Monetary value of carbon dioxide in $

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6. Main future tasks and problems of desert research in solving the global problems of our time

Global problems of our time are basically human ecological ones with the interplay of environmental and social factors. The most important global crisis phenomena are closely connected with each other, form a coherent system, and are associated with the anthropogenic disorders of the healthy functioning of the biosphere.

Main crisis phenomena are:

1. Global overpopulation crisis (population explosion),
2. Global climate change,
3. Global biodiversity crisis (mass extinction of species, habitat loss, the collapse of ecosystems),
4. Global social crisis (income scissors opening wider),
5. Global information crisis (insufficiency of scientific synthesis, overspecialization, publication flood), and
6. Lack of global coordination (independent influence of 195 nation states without substantive common planning and regulation).

Several of these problems are linked to the ecological research of deserts. Among the anthropogenic causes of desertification, overpopulation plays an important role; however, this

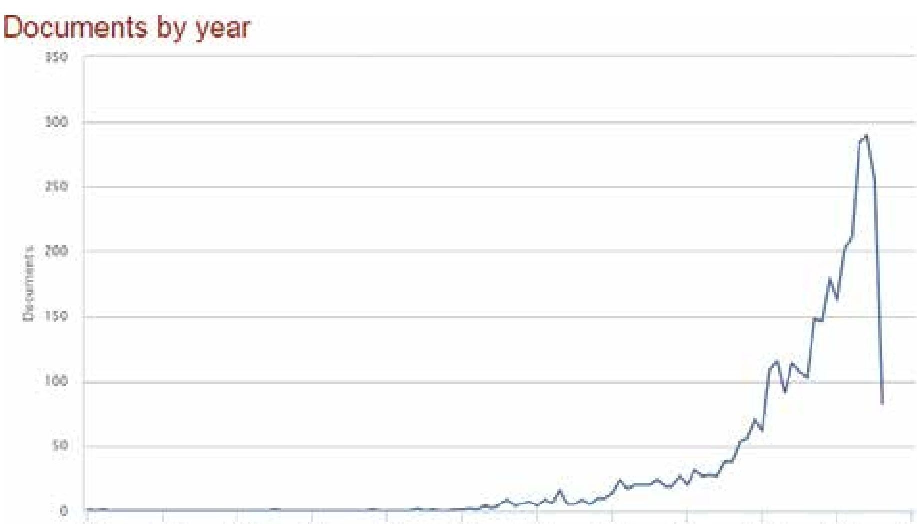

Figure 1. Number of articles with keywords desert + ecology in their abstracts in the Scopus database (downloaded on April 18, 2018).

increases the global social crisis as feedback. Global climate change is a cause and a consequence at the same time, since draught results in desertification, however, low plant production decreases carbon sequestration, which further enhances climate change. This group of phenomena is apparently closely connected with the biodiversity crisis also as a cause and an effect. Global information crisis makes itself felt in this area as well, since new data and knowledge are increasing exponentially, see **Figure 1**. It shows the yearly number of international scientific articles with keywords desert + ecology in their abstracts according to the Scopus database, for the period 1912–2018 (downloaded on April 18, 2018, thus data for 2018 are quarterly ones).

When examining the genre of these publication data (rate of document types, **Figure 2**), one can see that 90.7% of the publications are made up of primary publications (journal articles) and pre-publication (conference papers), and only 7.4% of them is synthesis (review articles, book chapters, or books). Thus, new information is produced much faster than we can organize it into a system of thought.

Solving global problems (among them desertification problems) of mankind is mainly hindered by the lack of global coordination, which would serve the protection of the common interest and align the efforts of mankind. Solving global problems needs efficient international cooperation, aligned scientific research, aligned political decision-making, legislation and economic regulation.

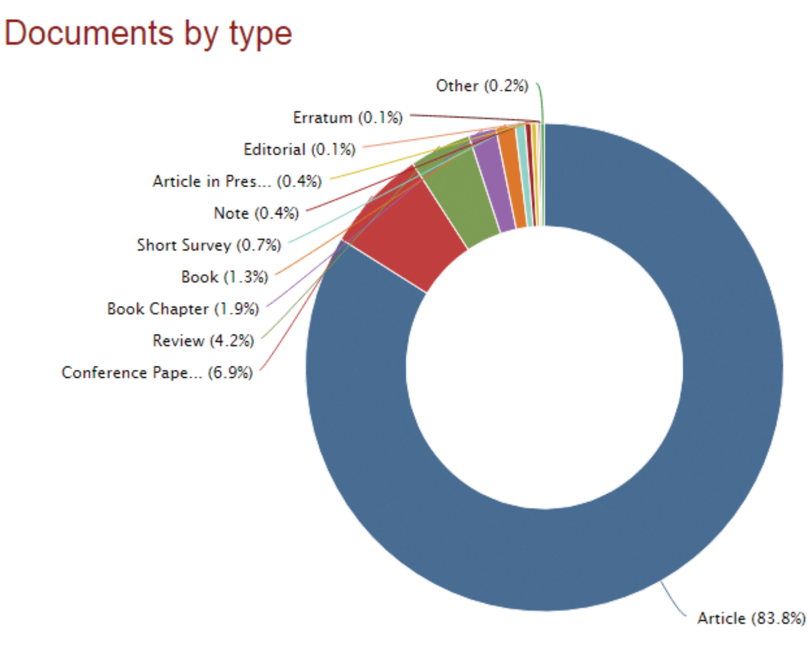

Figure 2. Distribution of articles with keywords desert + ecology in their abstracts according to a document type in the Scopus database (downloaded on April 18, 2018).

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Chapter 2

The Impact of Desertification Dynamics on Regional Ecosystem Services: A Case Study of Inner Mongolia (China)

Duanyang Xu

Additional information is available at the end of the chapter

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Abstract

As one of the most important ecosystems of our planet, desert and desertified land have provided critical ecosystem services to support inhabitants of dry lands, and the desertification dynamics would have greatly impact on regional ecosystem services and economical-social development. In this study, the desertification dynamics in Inner Mongolia, China, and its impact on regional ecosystem services were analyzed by combining multisource data, GIS, and sensitivity analysis method. The results showed that the total ecosystem service value (ESV) decreased by 67.16 billion yuan from 1981 to 2010, and desertification dynamics had moderate linear correlation with ESV, which caused 23.7% decrease of ESV. The impacts of desertification dynamics on the change of ESV in different subregions had spatial heterogeneity, which had promoting effects in southwest of Inner Mongolia and reverse effects in northeast subregions. The sensitivity of ESV to desertification dynamics in different subregions also had obvious differences, and subregions with higher vegetation coverage always showed larger SAF (sensitivity coefficient). Different measures, such as reasonably utilizing water and soil resources, adopting water-saving technology, adjusting the industry structure, and developing the ecological industry, should be adopted by the government to control desertification and promote the ecosystem services.

Keywords: desertification, ecosystem service, impact, sensitivity, Inner Mongolia

1. Introduction

Desertification is land degradation in arid, semiarid, and dry subhumid areas resulting from various factors, including climatic variations and human activities [1, 2]. Desertification has been treated as one of the most serious social-economic-environmental issues in our world, the total area affected by desertification reaches 6–12 million km^2, and about 1–6% of inhabitants of dry land live in desertified area [3]. The long-term intensive use and consume of land and vegetation resources, such as overgrazing, overcutting, excessive reclamation, and rapid urbanization, together with the climate change, made desertification expanded greatly in the globe over the past century, especially for the Sahel in Central and Northern Africa, Mediterranean region, Central and Western Asia, and North China [4–6]. For example, an analysis of a time series of remote sensing images between 1981 and 2003 revealed a persistently declining productivity throughout this period on over 20% of the global land, which had impact on 1.5 billion people [7].

As one of the most important ecosystems and land cover types in the planet, deserts and desertified land also provide some critical ecosystem services to support their inhabitants and economic-social development, including carbon fixation and oxygen release, hydrological regulation, soil conservation and sand fixation, biodiversity maintenance, and ecological tourism [8, 9], which create ecological and economic value [10, 11]. And, the desertification expansion would lead to the loss of ecosystem services and economy; research sponsored by the United Nations Environment Programme showed that the global economic losses caused by desertification and drought were as high as US $\$4.2 \times 10^{10}$ each year, which was equivalent to all official aid to Africa in 2009 [12]. The reduction of ecosystem services and land production induced by desertification would have a great impact on the sustainable livelihoods of people living in rural community [13]; especially under the background of global warming and urbanization, the risk of land desertification and its potential impact on rural people would become higher and higher [14]. So, effectively control of desertification requires long-term systematic efforts aimed at restoring the functions of desert ecosystem services to realize the securing of both ecological and economic benefits. This will not only require the investment of large amounts of money and new technologies but also need the identification and effort of local people [15].

Over the past few decades, deserts and desertified land have changed greatly due to climate change and human activities, which had resulted in a significant alteration to these areas' global and regional ecosystem services [16–18]. In the process of desertification reversion, the dominant species, plant community structure, and landscape pattern change significantly; annuals gradually evolve into shrubs and perennial herbs, and the species richness, vegetation coverage, and landscape heterogeneity increase; and the soil sand content decreases, as well [19, 20]. All these changes might lead to the enhancement of ecosystem services. For example, a previous study in Yuyang District, Shaanxi Province, China, showed that the Project of Returning Farmland to Forest and other ecological measures had led to an increase in the regional sand stabilization function value of 5.64×10^6 yuan per year from 1988 to 2003 [21]. However, in the process of desertification expansion, vegetation is destroyed, and more soils are exposed to the air, which will increase the risk of wind erosion and make sand hill active, and then lead to the decrease of ecosystem services, especially for the sand fixation function and service. Research conducted by Ben Mariem and Chaieb had shown that the suitable habitat for alfa grass in Tunisia had increased greatly with the increase in greenhouse gas, which would lead the reduction of ecosystem services provided by dry lands [22]. So, scholars have gained that a more consistent understanding of that increasing vegetation coverage can provide an effective measure to improve the ecosystem services in dry land [23].

Identifying and measuring the impact of desertification dynamics on regional ecosystem services is an effective way to assess the costs and benefits to the environment and support sustainable land management decisions in the rural community [24]. Accounting the ecosystem service value (ESV) is useful to analyze the impact of land use and land cover change [25, 26], including desertification dynamics, on regional ecosystem services. For example, Costanza et al. [27] and Daily et al. [28] estimated the global ESV by using a market valuation method, which made it possible to quantitatively analyze and compare the change in the ecosystem services. Ouyang et al. [29] assessed the value of terrestrial ecosystem services in China, including desert ecosystems. Xie et al. [30, 31] established and improved a service value table for desert ecosystems, which had important guiding significance for later studies in China. Yirsaw et al. [32] had analyzed the effect of temporal land use/land cover changes on ecosystem services in coastal area of China. However, these studies always underestimated the importance of the ecosystem services provided by deserts and desertified land, and less attention has been paid to the impact of desertification dynamics on the regional ecosystem services, which might lead to a misunderstanding of the effect of desertification control and sustainable land management in rural community.

China is one of the countries that is seriously affected by desertification in the world. According to the fifth desertification survey statistics of the State Forestry Administration of the People's Republic of China, the desertified area in China reached 2,611,600 km^2 in 2014, which accounted for 27.20% of the country's total land area [33]. Inner Mongolia autonomous region (hereinafter referred to as Inner Mongolia) is a representative ecologically fragile area in North China and seriously affected by desertification. Combating desertification and promoting the ecosystem services in this region are playing a critical role in guaranteeing the ecological security of North China. Although a great deal of ecological protect projects and polices, such as Three-North Shelterbelt Project, Beijing-Tianjin Sandstorm Source Treatment Project, Grain for Green Project [34, 35], no grazing policy [36, 37], have been carried out in recent years, extensive human activities such as mining and rapid urbanization still have a great impact on the vegetation cover and desertification [38, 39]. These factors coupled with climate change have generated significant changes in the desertification and ecosystem services of Inner Mongolia. So, it is necessary and meaningful to investigate the desertification dynamics and assess their impact on regional ecosystem services, which can provide support for policy-makers and land managers involved in desertification control and ecology rehabilitation in arid areas.

2. Materials and methods

2.1. Study area

Inner Mongolia lies between 37°24′N–53°23′N and 97°12′E–126°04′E in North China and includes a total of 88 counties or banners (hereinafter referred to as counties; **Figure 1**).

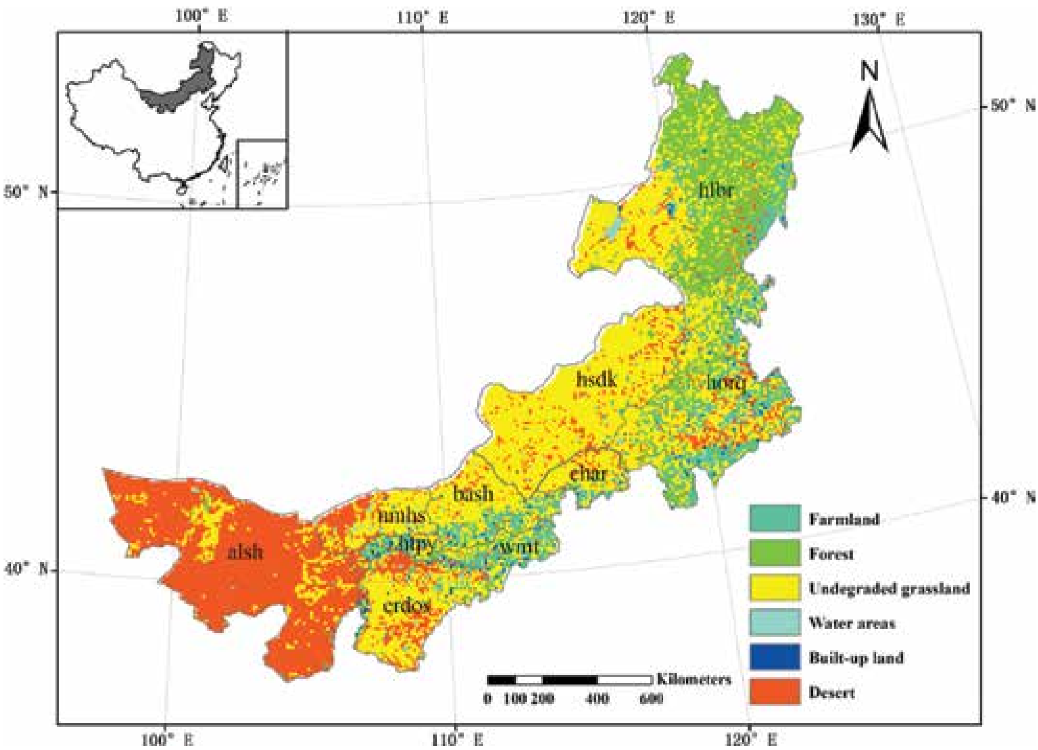

Figure 1. The area of study.

The study area covered approximately 1.18 × 10^6 km^2 or 12.3% of the country's total area. The temperate zone continental monsoon climate has an average temperature of 0–8°C and an annual total precipitation of 50–450 mm that progressively decreased from east to west. The region receives an average annual of 2850 h of sunshine and stands at an average elevation of 1000 m. The soils are mostly brown desert, chestnut, and sandy soils. Gales occur on 10–40 days annually, mainly in spring, and 5–20 days with sandstorms. Influenced by climatic factors (such as sandstorms, temperature, precipitation, etc.) and unsustainable human activities (such as grassland reclamation, abandonment of cultivated land, etc.), desertification become a serious problem in this region. To facilitate statistical and comparative analyses, the study area was divided into 10 subregions according to the climate characteristics and natural geography [40], including the Hulun Buir grassland (hlbr), Horqin grassland (horq), Hunshandake sandy land (hsdk), Chahar grassland (char), Bashang area (bash), Wumeng Qianshan and Tumote plain (wmt), Houshan region in Inner Mongolia (nmhs), Hetao plain (htpy), Erdos grassland (erdos), and Alashan plateau (alsh).

2.2. Data collection and process

The data used in this study included NDVI (normalized difference vegetation index) data, land use data, high-resolution remote sensing images, and other auxiliary data. NDVI used in this study was the Global Inventory Modeling and Mapping Studies (NDVI3g) dataset, with these data obtained from the National Aeronautics and Space Administration. The time resolution of this dataset was half a month with a spatial resolution of 8 km and the time range of 1981–2010. This dataset has been preprocessed by geometric correction and graphic enhancement to ensure data quality. The land use data in 1980s and 2010s with an accuracy of 1 km was derived from the Chinese Academy of Sciences Resource and Environmental Data Center, and the national county-level administrative maps used to generate the boundary data of the study area came from the National Geomatics Center of China. The Landsat TM/ETM images covering the study area came from the United States Geological Survey (USGS) and Google Earth. Auxiliary data, such as meteorological and statistical information, were also collected from the National Meteorological Information Center and the national and regional Statistical Yearbooks. To facilitate spatial analysis and comparison, all the grid and vector data used in this study were resampled or converted into grid data with an 8 km resolution.

2.3. Methods

2.3.1. Land classification and desertification monitoring

To analyze the impacts of desertification on the regional ecosystem services, the land use and land cover of the study area were classified into two categories: deserts and desertified land and non-desertified land. According to the land use type, non-desertified land was further divided into farmland, forest, undegraded grassland, built-up land, and water areas. The deserts and desertified land were further divided into regions of low, medium, high, and severe desertification based on the degree of desertification. The NDVI data, land use map, and high-resolution images were used to classify the land use and land cover types. Our procedure was as follows: (1) We extracted non-desertified lands. A 1:100,000 land use map was used to identify farmland, forest, built-up land, and water areas. By combining high-resolution remote sensing maps from Google Earth and our field investigation, 100 sample points for each subregion were selected for undegraded grassland; the NDVI threshold value system was then used to extract the undegraded grassland. (2) We extracted deserts and desertified land with different grades. The method of undegraded grassland extraction involved the selection of 100 sample points for each subregion to identify the desert regions. Then, the NDVI threshold desertification value system for the lands (low, medium, high, and severe) was established by equal interval dividing the NDVI value between the deserts and undegraded grassland. To avoid classification errors caused by short-term climate fluctuations, the average NDVI values for nearly 3 years were used to extract the information about deserts and desertified land in 1981 and 2010. In this study, a visual inspection was conducted to correct the classification errors and adjust the threshold values. Fifty checkpoints were randomly selected in every subregion to verify the results, and the overall classification accuracy was more than 90%.

2.3.2. Assessing the impact of desertification dynamics on ecosystem services

In this study, the ESV was used as a proxy to measure the impact of desertification dynamics on regional ecosystem services. The ESV per unit area of each land category was compared with different biomes and assigned based on the results derived by Xie et al. [31], who had estimated the equivalent weight factors and modified the ESV coefficient per hectare of terrestrial ecosystems in China. To quantitatively assess the impact of land with different desertification degrees on the regional ESV, the ESV for the low, medium, high, and severely desertified lands was assigned by the use of the equal interval grading weight factor between the ESV of the deserts and undegraded grassland:

$$ESV = \sum_{i=1}^{n} P_{ij} \times A_i \tag{1}$$

where ESV is the total ecosystem service value of one region (10,000 yuan·km^{-2}·a^{-1}), P_{ij} is the adjusted ESV per unit area of land use and land cover type i (10,000 yuan·km^{-2}·a^{-1}), and A_{ij} is the area of land use and land cover type i (km^2).

We took into consideration the differences in the ESV provided by the same type of land use and land cover in different regions and introduced an adjusting factor in this study by biomass because the ESV always has a robust positive relationship with the biomass [41]:

$$P_{ij} = \left(b_j/B\right)P_i \tag{2}$$

where B_j is the biomass of the land use and land cover type i, which was replaced by the NDVI in this study. B is the average biomass of the land use and land cover type i in China, which was also calculated by NDVI; and P_i is basically the ESV per unit area of land use and land cover type i in China (10,000 yuan·km^{-2}·a^{-1}), which is shown in **Table 1**.

2.3.3. Sensitivity analysis

In this study, the sensitivity coefficient was conducted to assess the changing degrees of the regional ESV that was caused by desertification. The sensitivity coefficient (SAF) measured the sensitivity degree by comparing the changes in the ESV of the whole region to the deserts and desertified land from 1981 to 2010:

$$SAF = \frac{(VC' - VC)/VC}{(S' - S)/S} \tag{3}$$

where SAF is the sensitivity coefficient and higher values of $|SAF|$ indicate greater changes in the regional ESV caused by desertification; VC' is the regional ESV in 2010; VC is the regional ESV in 1981; S' is the ESV of the deserts and desertified lands in 2010; and S is the ESV of the deserts and desertified lands in 1981.

	Forest	Farmland	Water areas	Low desertification	Medium desertification	High desertification	Severe desertification	Desert
Total	126.29	35.48	203.67	47.17	39.31	26.21	18.34	6.24

Table 1. The ESV per unit area of different land types in Inner Mongolia (million yuan/km^2/a).

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3. Results

3.1. The desertification dynamic in Inner Mongolia from 1981 to 2010

From 1981 to 2010, the area of deserts and desertified land in Inner Mongolia expanded from 555.3 km^2 in 1981 to 624.5 km^2 in 2010. Except for a decrease of 28,000 km^2 in deserts, the area of land with low, medium, high, and severe desertification all showed different increases. The largest increment is caused by medium desertification, which increased 48.77% over 1981. Reversion and expansion between lands with different desertification degrees and between desertified and non-desertified lands are equally significant, which showed a significant spatial heterogeneity. In the 30 years, the area of desertification reversion in Inner Mongolia was 170,900 km^2, with an expansion area of 204,300 km^2 (**Figure 2**).

The area of desertification reversion was mainly distributed in erdos, alsh, bash, and other areas in southwest Inner Mongolia. Among them, the area of desertification reversion in erdos accounted for 8.71% of the desertified land area of Inner Mongolia. The area of desertification reversion in alsh and bash also reached 8.33 and 5.1% of the total desertification area, respectively. The reversal area among different degrees of desertification accounted for 17.98% of the total desertification area. The reversal area from deserts and desertified land to non-desertified

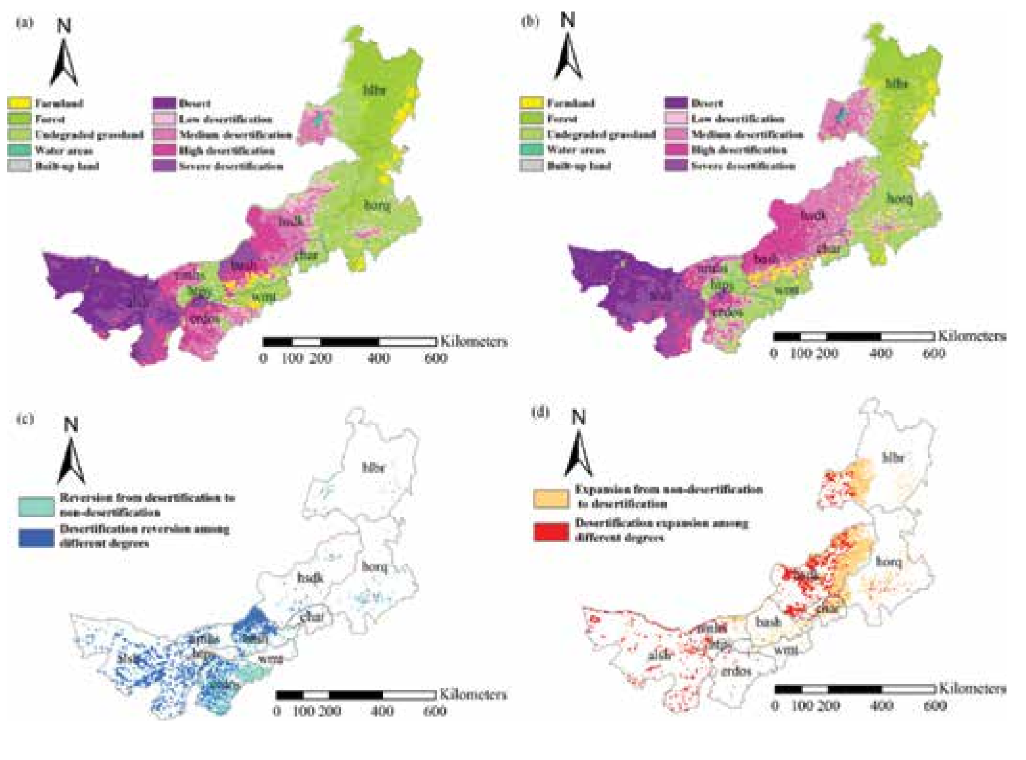

Figure 2. Land use and desertification change in Inner Mongolia autonomous region from 1980s to 2010s. (a) Land use and desertification map in 1981, (b) land use and desertification map in 2010, (c) desertification reversion and (d) desertification expansion.

lands accounts for 9.38% of total desertification area, which was dominated by the reversion to undegraded grassland. The expansion of desertification mainly occurred in central-northern Inner Mongolia, such as southwestern hlbr, hsdk, and char. The desertification expansion in hsdk accounted for the largest proportion of total desertification area, reaching 13.76%. The expansion area among differing degrees of desertification accounted for 12.28% of the whole deserts and desertified land, and the area of land that expanded from non-desertified lands to deserts and desertified land was nearly twice as much as the area of desertification expansion among different degrees, which was mainly attributed to the expansion from undegraded grassland to desertification.

3.2. Changes of the ESV in Inner Mongolia from 1981 to 2010

The total ESV of Inner Mongolia decreased 67.16 billion yuan from 1981 to 2010 (**Table 2**), which was equivalent to 5.74% of Inner Mongolia's GDP in 2010. For different land use types, the ESV of forest and undegraded grassland decreased significantly, and the ratio of the total value of the two ecosystems dropped from 52.02% in 1981 to 44.18% in 2010. In addition, the ESV of desert also showed a downward trend with a rate of change of −19.12%. The increase of ESV mainly occurred in farmland and desertified land, and the ESV of desertified land had increased 19.97 billion yuan.

The ESV in Inner Mongolia had illustrated a great spatial heterogeneity (**Figure 3**); the ESV in eastern and southern part was higher than western and northern part. The high value area (500–110 million yuan) was mainly located in hlbr, and the unit grid (64 km^2) ESV reached more than 50 million yuan, while the unit grid ESV in alsh located in the western of Inner Mongolia was less than 5 million yuan, which was mainly attributed to the zonal distribution of vegetation. Compared with 1981, the ESV in northeastern hsdk and central hlbr had

Land type	**ESV**		**The ecological value change**	**Rate (%)**
	1981	**2010**		
Forest	304.97	229.35	−75.62	−2.48
Undegraded grassland	181.65	160.28	−21.37	−1.18
Farmland	15.38	18.25	2.88	1.87
Water areas	7.80	15.19	7.40	9.49
Desert	2.19	1.77	−0.42	−1.91
Low desertification	22.69	23.91	1.22	0.54
Medium desertification	34.42	51.21	16.79	4.88
High desertification	12.54	14.12	1.58	1.26
Severe desertification	4.65	5.03	0.38	0.82
Total	586.28	519.12	−67.16	−1.15

Table 2. The total regional ESV and its change in Inner Mongolia between 1981 and 2010 (billion yuan).

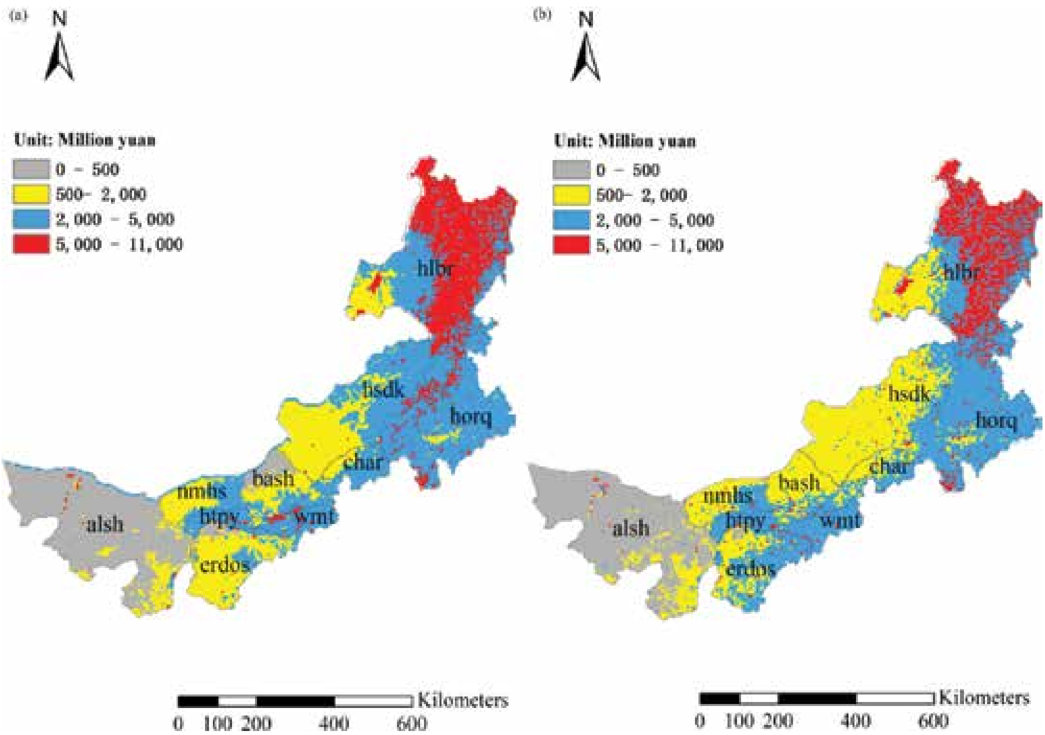

Figure 3. Spatial distribution of unit grid ESV in Inner Mongolia in 1981 and 2010. (a) 1981 and (b) 2010.

decreased in 2010, while the ESV in northeastern erdos had increased, and other regions did not change obviously.

3.3. The impact of desertification dynamics on regional ESV in Inner Mongolia

From 1981 to 2010, the desertification dynamic (reversion and expansion) in Inner Mongolia had a great impact on the whole regional ESV, which had led to a loss of 15.89 billion yuan of the ESV (**Tables 3** and **4**), accounting for 23.7% of the total loss. The Pearson correlation coefficient between the change of ESV and the change of ESV caused by desertification reached 0.63 ($p < 0.05$), which showed a moderate linear correlation between them.

The increment of the ESV caused by desertification reversion was 32.43 billion yuan, which accounted for 6.25% of the total ESV in 2010. The increment of the ESV caused by desertification reversion among different degrees reached 10.05 billion yuan, and the reversion of high desertification had led to an increment of 4.17 billion yuan. The increment of the ESV caused by reversion from deserts and desertified land to non-desertified lands was about 2.2 times as much as the increment of the ESV caused by reversion between lands with different desertification degrees, and the reversion from deserts and desertified land to undegraded grassland alone increased the ESV by 10.65 billion yuan. In terms of desertification expansion, expansion between lands with different desertification degrees had led to 10.17 billion yuan loss of ESV.

Value	Desertification reversion among different degrees	Reversion from desertification to non-desertification			
Change type		Forest	Undegraded grassland	Farmland	Water areas
Low desertification	—	2.20	1.72	0.05	0.83
Medium desertification	1.78	1.51	6.62	0.36	2.91
High desertification	4.17	0.82	2.13	0.51	0.80
Severe desertification	1.82	0.11	0.12	0.04	0.30
Desert	2.28	1.14	0.06	0	0.16

Table 3. The impact of desertification reversion on regional ESV (billion yuan).

Value	Desertification expansion among different degrees	Expansion from non-desertification to desertification			
Change type		Forest	Undegraded grassland	Farmland	Water areas
Low desertification	−6.32	−5.67	−4.40	−0.06	−0.28
Medium desertification	−3.00	−0.94	−21.24	−0.47	−0.39
High desertification	−0.53	0	−1.53	−0.05	−0.36
Severe desertification	−0.32	−0.32	−0.38	0	−0.30
Desert	—	−0.11	−0.13	−0.02	−1.50

Table 4. The impact of desertification expansion on regional ESV (billion yuan).

Among them, the impact of low and medium desertification expansion was more obvious. The area of expansion from non-desertified lands to deserts and desertified land was 127,700 km^2, which had led to 38.15 billion yuan loss of ESV, and was mainly induced by the expansion from forest and undegraded grassland to low and medium desertification.

3.4. Impact of desertification dynamics on regional ESV in different subregions

The impact of desertification dynamics on regional ESV at the subregion level showed a significant spatial heterogeneity. From 1981 to 2010, the ESV in bash, htpy, and erdos was increased, and the desertification dynamics played a promoting role in this increment, which meant the increment of ESV of deserts and desertified land led to the increase of regional ESV. The ESV in hlbr, hsdk, char, and horq showed a decreasing trend, and the desertification dynamics also showed a promoting effect, which was mainly attributed desertification expansion in these subregions. However, the desertification dynamics in wmt, nmhs, and alsh had an opposite effect on the change of regional ESV.

Subregion	The total ESV change (billion yuan)	ESV change caused by desertification dynamics (billion yuan)	Sensitivity coefficient (SAF)
hlbr	−39.38	−10.39	8.91E−8
hsdk	−18.19	−17.21	2.38
char	−2.26	−2.08	4.21
horq	−17.35	−41.77	74.53
bash	1.77	2.50	4.52
wmt	−1.56	1.00	−9.83
htpy	0..07	0.28	53.15
nmhs	0.20	−0.05	−0.57
erdos	12.18	12.02	1.36
alsh	−0.13	0.60	−6.12

Table 5. Sensitivity analysis of regional ESV to desertification dynamics.

In this study, sensitivity coefficient was introduced to quantitatively analyze the sensitivity of the regional ESV change to desertification dynamics, and the results of the sensitivity degree showed a great spatial heterogeneity (**Table 5**). The ESV in horq and htpy was very sensitive to desertification dynamics, and the sensitivity coefficient reached 74.53 and 53.15, respectively. However, both hlbr and nmhs showed the same or opposite sensitivities, the coefficients all hovered around 0, and the sensitivity was relatively small.

4. Discussion

As one of the most important land degradation types in dry land, desertification dynamics can bring a great impact on regional ecosystem service supply and sustainable livelihoods, especially for the people living in rural area. According to the Millennium Ecosystem Assessment (MEA), livelihood activities in dry land tend to be more dependent on available ecosystem services than elsewhere [42]. In order to enhance the ecosystem services and sustainable development in dry land, UNCCD had launched a policy strategy called “Zero Net Land Degradation” (ZNLD) in 2012, aiming to prevent the degradation of productive land and restore already degraded land by sustainable land management. To achieve these goals, we need to investigate the impact of desertification dynamics on regional ecosystem services at regional scale and identify the sensitive area to support the policy-making.

Due to the location and various driving factors, Inner Mongolia of China is a perfect place to study desertification dynamics and its impact on regional ecosystem services. According to our study, impacted by both climate change and human activities, desertification in Inner Mongolia had changed dramatically over the past three decades. Due to the implementation process of the “Three North” Shelterbelt Project, the Beijing-Tianjin sandstorm source project, and the Natural Forest Protection, the coverage of vegetation was increased, and some areas showed obvious desertification reversion [43], which made it possible to increase the ESV. In the same period, intensive human activities, such as coal mining, oil and gas drilling, road, subway, and pipeline laying, had promoted the economic development in rural areas and pastoral areas as well as destroy the vegetation in ecologically fragile regions with abundant resources; land desertification problem was more prominent [44], resulting in ESV loss. All factors mentioned above made the impact of desertification dynamics on regional ESV, which showed a great spatial heterogeneity.

The further investigation based on the sensitive analysis results showed that the desertification reversion in erdos and alsh had play a promoting role in the increment of regional ESV, which was mainly attributed to the ecological projects and policies implementation and ecology-based industry development. Taking alsh as an example, by developing the farming of *Haloxylon-Cistanche*, two genera of useful plants, the yield of *Cistanche* increased from 200 to 800–1000 tons per year in Inner Mongolia, which not only increased the income of farmers but also achieved the goal of combating desertification [45]. However, the ESV in nmhs and horq showed a significant decreasing trend, especially for horq, whose sensitive coefficient reached 74.53, and these regions should be the focus of desertification control in the future. For the ESV decrement areas which are less sensitive such as hlbr, more attention should be paid to protect and prevent damage. To avoid the reduction of forest and undegraded grassland area and quality decline, different measures, such as soil and water management and rational exploitation, improve the quality of population, and delineation of "ecological red line," should be implemented to ensure the regional ecological security.

The impact of desertification dynamics on regional ecosystem services was carried out by monetizing the value of different ecosystems, including deserts and desertified land. According to the equal interval principle, five desertification grades were divided. The low and medium desertified areas might overlap the grassland with a certain degree of desertification. Thus, compared with other research results [46, 47], the area and ESV of deserts and desertified land were higher, and the area and ESV of undegraded grassland were lower. However, the land classifications in this study could be used to objectively analyze the impact of different processes of desertification on regional ecosystem service change. In the future, data of climate change and human activities would be involved to quantify the mechanisms of the impact of desertification dynamics. Besides, the linkage of ecosystem service change and sustainable livelihoods of rural community should be further investigated, and the specific measures and policies for how to enhance the adaptive ability and resilience of rural community should be studied in the future.

5. Conclusion

From 1981 to 2010, the desertification dynamics in Inner Mongolia were obvious. The area of the lands that experienced desertification reversion was 170,900 km^2, which was mainly distributed in erdos, alsh, and other sand areas in the southwest. The area of the lands experiencing desertification expansion was 204,300 km^2, and these lands were mainly located in hsdk and other north-central sand areas. There was a significant spatial heterogeneity in the desertification reversion and expansion, and the main changes in the types of desertification were between adjacent desertification degrees.

Over the past 30 years, the ESV in the Inner Mongolia has decreased by 67.16 billion yuan. Compared with 1981, the ESV in the northeast hsdk, central hlbr decreased, and the ESV in the eastern erdos increased. Desertification dynamics had a great impact on regional ESV in Inner Mongolia, and the ESV decrement caused by desertification dynamics reached 15.89 billion yuan, accounting for 23.7% of the total value loss.

Desertification reversion and expansion on the ESV showed a spatial heterogeneity. The desertification dynamics had promoted the ESV change in bash and hlbr but played an opposite role in wmt and other places. The sensitivity of ESV to desertification was also different. Horq and htpy were more sensitive than other sub-regions, and the sensitivity of them were higher than 50. Hlbr and nmhs was less sensitive. To enhance economic development and the ecological service supply, "win-win" measures should be used for subregions with different sensitivities.

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Chapter 3

Behavioral and Reproductive Strategies of *Porcellio* Species (Oniscidea) in Tunisian Pre-Desert Ecosystems

Lamia Medini-Bouaziz

Additional information is available at the end of the chapter

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Abstract

Oniscids inhabiting xeric habitats are of particular interest because these habitats may be one of the important agents for desert soil fertility. Although numerous studies have examined the relationship between the environment and population ecology in woodlice that live in mesic habitats, very little is known about these desert species. Tunisia is known for its arid regions south of the Tunisian Dorsal, habitats in which several species of terrestrial isopods are well adapted. *Porcellio* is the most widely represented within these habitats: their species richness reaches eight in arid bioclimatic stage. The most widespread of the *Porcellio* is *P. buddelundi*, and the least widespread is *P. albicornis.* Behavioral and reproductive studies carried out in Zarat and Matmata on the two species *P. albinus* and *P. buddelundi* showed that the xeric *Porcellio* species are mainly active at night and they shelter from the extreme heat and dryness of their habitats either in burrows they dig or by vertical migration. The reproductive pattern is seasonal with two breeding seasons. Life history traits allow *P. buddelundi* to be an r-strategist and *P. albinus* a k-strategist. The latter displays a fairly developed social behavior, which allowed him to be the most evolved of *Porcellio.*

Keywords: terrestrial isopods, xeric species, arid environment, reproductive traits, behavior, abiotic factors

1. Introduction

Soil is a dynamic and complex system: its physical and chemical nature, with a porous structure, immense surface area, and extremely variable supply of organic materials, food, water, and chemicals, provides habitats for many living beings among which arthropods that make up an essential component. Five groups are chiefly represented: Isopoda, Myriapoda, Insecta, Acari, and Collembola [1]. The oniscoids (Oniscidea) with more than 3600 species belonging to 5 major taxonomic groups—Diplocheta, Tylida, Microcheta, Synocheta, and Crinocheta [2]—are an important component. Isopod species composition and diversity were studied in several habitats within the Mediterranean region. Terrestrial isopod community structure differs across habitat types (natural area, seminatural area, agroecosystems, and protected area), vegetation structure, and altitude [3–12].

During the last 30 years, great efforts have been made to understand the role of isopods as well as other invertebrates in soil processes and their interactions with the abiotic factors of soil function. These isopods are involved in the process of maintaining soil fertility. They are both "litter transformers" and "ecosystem engineers" [1]. First, these detritivores, like other invertebrates such as Myriapoda and Collembola, contribute to nutrient cycling through mechanical breakdown of plant litter, through biochemical changes in organic matter during digestive transit, and by regulating soil microbial activity [13]. Second, these ecosystem engineers as many other arthropods affect the structural properties of soils ensuring adequate nutrient retention, aeration, and water-holding capacity below ground, facilitate root penetration, and prevent surface crusting and erosion of topsoil. However, most of the studies concerning the contribution of isopods to nutrient cycling have focused on soils in mesic habitats of temperate regions [13–15]. In drier warmer areas of the world, particular attention was addressed to termites and ants as well as to their constructions which affect soil processes by increasing soil porosity and infiltration, reducing or increasing bulk density, altering soil erosion by depositing subsoil on the surface, and altering the concentration and spatial distribution of soil nutrients [1, 16]. Among desert isopods, the role of the burrowing species *Hemilepistus reaumurii* in maintaining soil fertility in arid regions has been well studied. The results of field observations and feeding experiments in the laboratory show that annual ingestion was 3–12% of the available dead organic matter [17] and soil turnover 2–41 g m^{-2} depending on the soil type and site conditions [1]. *H. reaumurii* by ingestion and defecation of organic matter and inorganic soil particles alters the structure of the decomposition substrate and increase the rate of decomposition in the desert ecosystem [17].

Besides their importance in maintaining ecosystem integrity, woodlice represent a remarkable group of crustaceans due to their high degree of terrestrialization [18]. These Oniscidae originally arising from the aquatic environment became terrestrial during the second half of the Paleozoic era [19]. They have evolved into a wide diversity of terrestrial species that have successfully colonized a wide range of habitats ranging from supralittoral levels (*Ligia* [20]) to mountains (*Porcellio djahizi* [21]) and desert ecosystems [22–24].

According to Sutton et al. [25], the successful colonization of the entire terrestrial globe by Oniscidea is explained by their flexible reproduction (onset and duration of the reproduction period) and its demographic parameters (longevity, age at sexual maturity, number of brood, etc.) that help them overcome the influence of the biotic and abiotic environmental factors to which they are subjected. Temperature, precipitation regime, and photoperiod are important factors regulating the reproduction of terrestrial isopods [26, 27], resulting in temporal coincidences of the release of the mancae with favorable conditions for growth and survival. This could explain the different reproductive patterns observed in terrestrial isopods: the majority of tropical and subtropical species have continuous reproduction [28–30], while temperate has a seasonal breeding followed by a period of sexual rest. The information available on terrestrial isopod reproduction patterns in temperate regions is largely for species occupying mesic habitats [31–42]. The reproductive phenology of xeric species in temperate regions has been studied extensively only for populations in the Middle East desert [32, 43–45]. These desert species that are well adapted to an arid environment differ considerably in their breeding seasons and strategies [46]. The burrowing species *Hemilepistus reaumurii* and *Hemilepistus klugii* are semelparous and reproduce during a very short time of the year: April and May for *H. reaumurii* and April for *H. klugii*. The other xeric species, which do not live in the burrows, are iteroparous. These are *Porcellio ficulneus* and *Porcellio barroisi*, which breed in spring, and *Armadillo albomarginatus*, which breeds in autumn. Both *Porcellio olivieri* and *Agabiformius obtusus* show continuous reproduction under laboratory conditions. Reproductive success in these terrestrial isopods depends on the largest size and number of offspring a female may have. The females of terrestrial isopods produce eggs and develop, following a parturial molt, a marsupium, which is not only a pouch for carrying eggs but plays the same role as a uterus that provides a transfer of substances between the female and its brood [47]. These activities require high energy costs for its offspring [48] that limit the future reproductive potential of the female. Given these constraints, better reproductive success can be achieved by extending care to offspring. Investing in already expensive offspring may be a better choice [44]. This hypothesis seems to explain the high parental investment of some terrestrial isopods in arid regions. The semelparous and burrowing species *H. reaumurii* shows two-parental care with sustainable family cohesion [2]. Indeed, the parental energy investment continues for several months after mancae release, until the young isopods disperse.

Oniscoids have succeeded, thanks to a number of adaptations noted above, to become the only large group of crustaceans to be completely terrestrial. Among them, Species that do not have effective protection against desiccation have been restricted to mesic habitats [49]. However, other species have managed to colonize semiarid and arid habitats, and some have even managed to thrive in the desert. These adaptations have made the nine species of *Hemilepistus* the most abundant detritivores of the macrofauna of many arid areas of Asia Minor [26, 45, 50]. All of them are burrowing species. The model species *H. reaumurii*, widely distributed in North Africa, is an isopod, physiologically and morphologically, well adapted to terrestrial life with its respiratory organs [51], its water balance, and its resistance to temperature [52, 53]. However, based solely on these adaptations, the species could not exist in the current biotopes. His great success is due, firstly, to his behavioral adaptations—his social character [44, 54] and his orientation [55]—and secondly to his reproductive strategy: *H. reaumurii* as *H. klugii* is semelparous and reproduces during a very short time of the year, April and May for the first species and April for the second [44, 45].

In the case of Tunisia, *H. reaumurii* can occupy the same xeric habitat as many other Oniscidea such as *Porcellio* species. In this genus, several studies have been conducted only on widely distributed and very frequent species. These studies focused on morphology [21, 56, 57], reproductive cycles [28, 40, 41, 58], enzymatic polymorphism [59], and Infection with the feminizing *Wolbachia* bacterium [60]. Little is known about xeric species.

Knowledge about the xeric species of *Porcellio* is still limited to their systematic [61–64], and only partial information is available on their reproductive and behavioral strategies

[44]. Based on the results obtained by the different studies carried out on the reproductive phenology of the desert species of the Middle East and based on the knowledge acquired in the *H. reaumurii* model terrestrial species, it is envisaged:

- To closely study the reproductive model of the semidesert species *P. buddelundi* and desert *P. albinus*.
- To verify the hypothesis of a single breeding season observed in Middle East desert species.
- To analyze the burrowing behavior of *P. albinus* and to identify its locomotor activity rhythm, in order to understand the behavioral mechanisms of adaptations of this species to the xeric conditions.

2. Desert *Porcellio* species and their geographical distribution

Despite its small size (163,610 km^2), Tunisia has 1300 km of coast on the Mediterranean Sea and is characterized by climatic, geological, and relief diversity. It is comprised of wetlands (5%), cultivated land (32%), nearly 13% forests, and about 40% desert lands. The arid regions

Figure 1. Geographical distribution of *Porcellio simulator* and *Porcellio albicornis* in Tunisia.

extend south of the Tunisian Dorsal from Sfax to Douiret in Tataouine. The climate of pre-Saharan Tunisia is located in the Mediterranean isoclimatic zone which can be defined, from an ecological point of view, as a climate of temperate zone, thus with seasonal and daily photoperiodism and with rainfall concentrated during the cold or relatively cold season (less than 200 mm/year), summer being dry [64].

This great ecosystem diversity has allowed the installation of several species of terrestrial Isopods, and the most recent assessments point to more than 40 species of oniscoids (Charfi-Cheikhrouha et al., unpublished). The *Porcellio* list, assessed by Medini-Bouaziz as 12 species in 2002 (*P. laevis*, *P. variabilis*, *P. dominici*, *P. marginenotatus*, *P. spatulatus*, *P. albicornis*, *P. lamellatus*, *P. djahizi*, *P. simulator*, *P. buddelundi*, *P. olivieri*, and *P. albinus*), was enlarged by the discovery of a 13th species *Porcellio wagneri*, which was first reported in Tunisia by Hamaied et al. (unpublished). The high species richness of *Porcellio* is reached in arid bioclimatic stages (eight species). The xeric species are quite numerous, representing more than a third of all *Porcellio* reported in Tunisia. These pre-desert and desert species belong to two distinct geographical groups of *Porcellio*: the North African group or laevis group and the group bético-rifain or group Hoffmanseggi. The former is represented by four of the five species reported in Tunisia (*P. simulator*, *P. olivieri*, *P. albicornis*, and *P. albinus*) and the last one by species *P. buddelundi* [64].

Figure 2. Geographical distribution of *Porcellio buddelundi* in Tunisia.

2.1. Geographical distribution in the world and in Tunisia

Xeric species, confined to the pre-Saharan Tunisia, are spread south of the Tunisian Dorsal corresponding to the eastern extension of the Saharan Atlas, as follows:

- *Porcellio simulator* is a North African species; its populations cover the center of Algeria [50] and occupy the center-west sector in the region of the high steppes in Tunisia [57] (**Figure 1**).
- *Porcellio buddelundi* and *Porcellio albicornis* show a narrow distribution area that is restricted to Sicily and circum-Sicilian islands in Italy [62] and in Tunisia [23, 64]. In Tunisia, the distribution of *P. buddelundi* covers Jeffara, the plains of Kairouan, and the high Tunisian steppes, while the presence *of P. albicornis* has been reported in the regions of Gabes and Kebili (**Figure 2**).
- *Porcellio olivieri* has a wide geographical distribution area that covers North Africa including Morocco [63], Algeria [65, 66], Libya [63, 67] as well as Egypt [49, 63, 65], and the Middle East [65, 68]. Described as an eastern desert species, *Porcellio olivieri* is found in Tunisia, in the Jeffara regions, in the southern lowlands, and in the southern Sahel (**Figure 3**).

Figure 3. Geographical distribution of *Porcellio olivieri* in Tunisia.

Figure 4. Geographical distribution of *Porcellio albinus* in Tunisia.

Figure 5. *Porcellio buddelundi.*

Figure 6. *Porcellio albinus.*

- The distribution area of *P. albinus*, the only burrowing species of the genus in Tunisia, is less extensive than that of *P. olivieri*. Its geographical distribution covers the North African Sahara, the Canary Islands [67], and the Niger Sahara [44]. In Tunisia, *P. albinus* occupies the regions of Jeffara and Nefzaoua and the southern lowlands. The expansion of this species to the north stops south of the Gafsa region (**Figure 4**). *Porcellio albinus* as *P. albicornis* is one of the rare species adapted to arid and Saharan habitats [64, 69].

2.2. Biotopes

The distribution of the xeric species correlates to stone coverage with the exception of both species *Porcellio albicornis* and *Porcellio albinus*, which live in sandy soil irrespective of stone coverage. The three pre-desert species *P. simulator*, *P. buddelundi*, and *P. olivieri* dwell in rocky areas (reg) which is home to various types of garrigue vegetation, including *Artemisia, Rosmarinus, Stipa,* and *Lygeum*; they rarely share the same habitat. The other two species, *P. albinus* and *P. albicornis*, were found in sandy nebkhas covered by desert vegetation species such as *Stipagrostis pungens, Astragalus armatus*, *Zygophyllum album*, and *Calicotome villosa*. However, *P. albicornis* may occupy another type of biotope that corresponds to a dry wadi rich in *Limoniastrum monopetalum* and *Peganum harmala* where he lives in sympatry with *Hemilepistus reaumurii*.

The two *Porcellio* we investigated in this chapter are *P. buddelundi* and *P. albinus* (**Figures 5** and **6**). Both species were collected at two different sites.

The population of *P. buddelundi* was collected at Oued El Jir, Matmata (Gabès), in the southeast of Tunisia (33°31′34″N, 10°7′19″ E (DMS)) (**Figure 7**). The habitat corresponds to a bare stony “reg” (**Figure 8**), and the soil is silt-clay type. This silt-clay structure is characterized by its high water

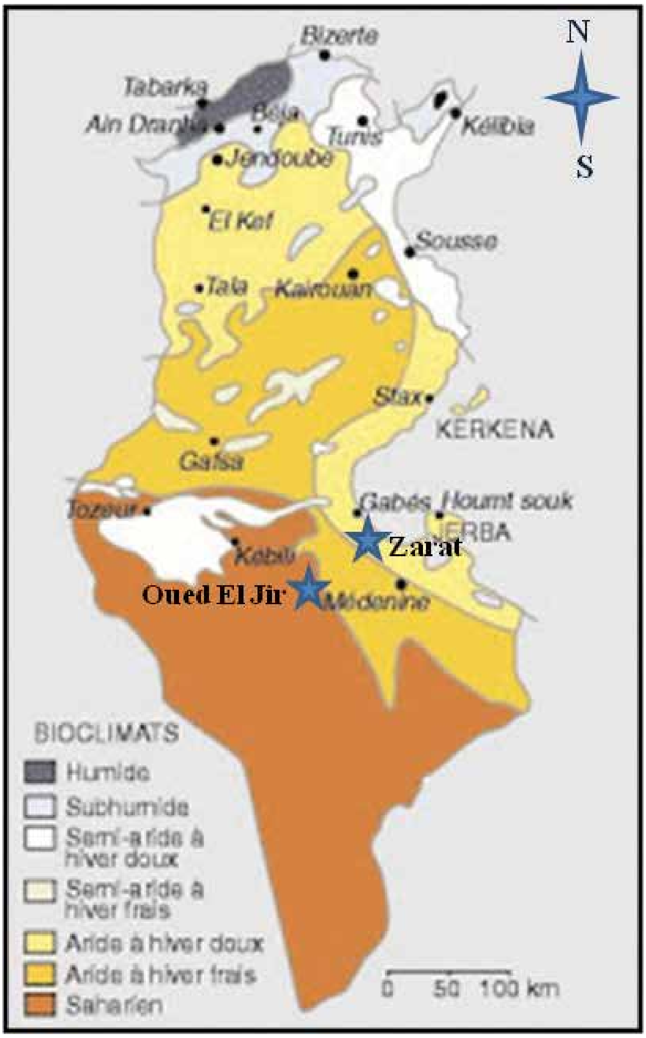

Figure 7. Sampling sites.

retention capacity and consequently high residual moisture content. In fact this criterion and the slightly alkaline pH of the soil (pH = 7.83) favor the survival of this species in a desert environment. Oued El Jir homes various types of garrigue vegetation, including *Artemisia*, *Rosmarinus*, *Stipa*, and *Lygeum*. The Köppen-Geiger climate map classified Matmata climate as BSh type. The climate in this area is characterized by an annual mean temperature of 18.9°C and a moderate annual temperature range (9–28.6°C) (**Table 1**). The total annual rainfall is 209 mm, and the variation in the precipitation between the driest and the wettest month is 34 mm (**Table 1**).

For *P. albinus*, the sampling site was the coastal area of Zarat, South of Gabes, Tunisia (33°40′N, 10°21′E (DMS)) (**Figure 7**); it corresponds to a marine sebkha environment [70]. The habitat is dominated by nebkhas corresponding to an accumulation of sand brought by the wind and trapped by vegetation (**Figure 9**). The vegetation was mainly composed of desert-adapted species

Figure 8. Biotope (Reg) of *Porcellio buddelundi.*

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Mean temperature (°C)	9	10.6	13.7	17.7	21.2	25.3	28.6	28.4	25.9	21.1	15.3	10.2
Minimum temperature (°C)	4.2	5.2	8	11.7	15.1	19.2	21.8	21.7	19.8	15.5	9.9	5.3
Maximum temperature (°C)	13.9	16.1	19.5	23.7	27.3	31.4	35.4	35.1	32.1	26.7	20.7	15.2
Rainfall	28	24	35	16	11	3	1	3	13	24	28	23

Table 1. Matmata temperature and precipitation.

Figure 9. Biotope (nebkhas) of *Porcellio albinus.*

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Mean temperature (°C)	11.7	12.9	15.3	18.3	21.8	25.1	27.7	28.1	26.3	22.2	16.9	12.8
Minimum temperature (°C)	7	7.7	9.9	12.8	16.2	19.6	21.6	22.1	20.7	17	11.8	8.1
Maximum temperature (°C)	16.4	18.1	20.8	23.9	27.4	30.6	33.9	34.2	31.9	27.6	22.1	17.6
Rainfall	19	17	20	15	7	2	0	1	16	35	23	23

Table 2. Zarat temperature and precipitation.

restricted to arid areas such as *Stipagrostis pungens*, *Astragalus armatus*, *Zygophyllum album*, and *Calicotome villosa*. The climate at Zarat is considered to be BWh by the Köppen-Geiger climate classification. Zarat climate is characterized by an annual rainfall of 178 mm and a difference in precipitation between the driest and the wettest month of 35 mm (**Table 2**). The average annual temperature is 19.9°C, and the annual temperature range is about 16.4°C (**Table 2**).

3. Reproductive traits comparison of *Porcellio albinus* and *Porcellio buddelundi* in pre-desert habitats

In North Africa, only the xeric species *Armadillo officinalis* from Libya [71] and *Hemilepistus reaumurii* from Tunisia [72, 73] have been the subject of study on reproductive phenology. These studies confirmed seasonal reproduction of temperate region species. Considering this element and what has been reported for the xeric Oniscidea of the Middle East in the introduction, two *Porcellio* species from the arid regions (*P. buddelundi* and *P. albinus*) were chosen on the basis of their geographical distribution in Tunisia (quite large in the case of *P. buddelundi* and more restricted in *P. albinus*) and their burrow digging (non-burrow digging *P. buddelundi* and *P. albinus* burrowing species). Both species are expected to have seasonal breeding, based on studies of reproductive phenology performed on temperate oniscoids.

3.1. Breeding phenology

The two *Porcellio* we investigated on Tunisia area were studied in the field. To study the breeding pattern of both species, a sampling of almost 100 specimens of *P. buddelundi* and about 60 specimens of *P. albinus* took place during 12 consecutive months for the former and 17 months for the latter. See Medini-Bouaziz et al. [22, 23] for further details on material and methods.

Sexual maturity was reached at about 14 mm in size during the first year of life (9 months) in females *of P. albinus* and at 41.1 mg of body mass in those of *P. buddelundi*. Considering this and the mean ovigerous female size (17.38 ± 1.8 mm), females of *P. albinus* cannot reproduce until the second year of their life. Those of *P. buddelundi* reproduce when they reach or exceed 70 mg body mass.

For both species, breeding starts in March and two breeding activities are defined (**Figure 10**). The first and the most important one was in spring, from March to June in the Zarat population of *P. albinus* and from March to May in Matmata population of *P. buddelundi*. The second was in the fall during the month of September in the first population and from September to October in the second one.

3.2. Fecundity, fertility and reproductive allocation

Fecundity estimated by the number of marsupial eggs was lower in *P. albinus* (36.3 ± 13.8 eggs) than that in the *P. buddelundi* species (60.9 ± 3.5 eggs). In the latter species, Medini-Bouaziz et al. [22] have shown that fecundity increases more with increasing ovigerous female body mass in spring than in autumn. A positive correlation between ovigerous female size and fecundity is noted in both species [22, 24].

Based on the study of fertility (number of mancae released from the marsupium) and the energy allocated to reproduction for each of the two species (**Table 3**), different tradeoffs were highlighted. The pre-desert species *P. buddelundi* generates a large number of small progeny (53.13 ± 3.2 mancae; newborn body mass = 0.44 ± 0.21 mg), whereas *P. albinus* produces few large offspring (19 ± 9 mancae; newborn body mass = 1.44 ± 0.75 mg).

3.3. Care of progeny

Of the two species studied, only *P. albinus* is able to provide care to his offspring. As reported by Medini-Bouaziz et al. [22], the study of the population dynamics of *P. albinus* in Zarat revealed, in all samples taken at night outside the burrows, predominance of larger specimens due to the absence of individuals whose size is smaller than 8 mm. Indeed, after the mancae release and during the first 2 months of life, newborns do not leave the family burrow. During this sensitive period, they depend on their brood-caring mother who provides

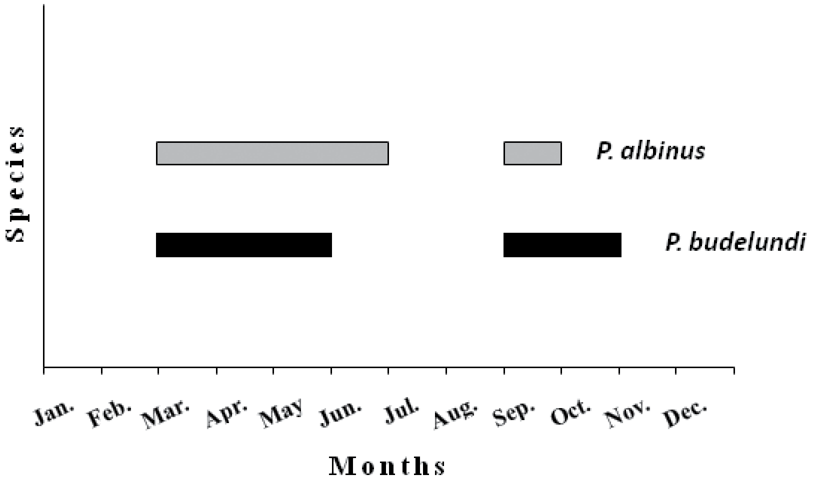

Figure 10. Reproductive activities of *Porcellio albinus* and *Porcellio buddelundi.*

them with food and defends them against predators. At the age of 2 months (size 8 mm), the young emerge for the first time from the burrow to forage.

Besides these results, the digging of about 30 burrows during the spring breeding season, carried out during the day when the animals are inside their burrows, revealed that these burrows contain either adults over 14 mm in size (one or two males/burrow, one female/burrow, a couple/burrow) or an adult female with several mancae or juveniles less than 12.5 mm in size. The number of these young in the burrows ranges between 3 and 35 individuals with an average number of 15 ± 10 pulli or juveniles/burrow. This indicates that the young of *P. albinus* remain in their natal burrow and do not disperse until they reach sexual maturity.

3.4. Life history traits comparison of *Porcellio albinus* and *Porcellio buddelundi*

The study of life history strategies integrates physiological, morphological, and behavioral traits to explain how organisms allocate finite resources to maintenance, growth, and reproduction, under predictable and unpredictable environments [74]. Thus life history patterns, evolved by natural selection, represent an optimization of tradeoffs between growth, survival, and reproduction. One major tradeoff could be between the number of offspring produced and the amount of energy allocated to each one. The timing of the first reproduction is another tradeoff; early reproduction reduces the chances of dying without offspring, but late reproduction can provide healthier offspring or better care. Members of some species breed only once (semelparity), while members of other species can breed several times (iteroparity). The choice of the appropriate strategy may be related to the degree of habitat specialization. Habitat specialists have often shown K-selected traits, while habitat generalists have shown r-selected traits. The xeric species *P. albinus* and *P. buddelundi* well adapted to arid environment differ considerably in their life history traits. These life history traits are summarized in **Table 3**.

To shelter from the extreme heat and dryness in arid environments, *P. albinus* digs burrows, while *P. buddelundi* performs a vertical migration. Both species are iteroparous and started their breeding activity in March with two breeding seasons. The length of the reproductive activity of *P. albinus* longer than 1 month in spring and less than 1 month in autumn than that of *P. buddelundi*. *P. albinus* has a longer development time, and sexual maturity is reached late, at 9 months old, which represents more than a third (37.5%) of its lifetime. *P. buddelundi* grows faster and reaches sexual maturity at 3–3.5 months old which corresponds to almost 20% of its lifetime. In *P. albinus*, there was no difference between ages of oldest female (largest female) and the largest reproductive females. This indicates that in this species, females were able to reproduce until their death, while in *P. buddelundi*, there is a difference between largest female (18 months) and largest reproductive female (12 months) because largest females in this species were not reproductive. *P. albinus* and *P. buddelundi* have a similar length of breeding period at the first brood: 28–35 and 28–33 days, respectively (**Table 3**). Although females of *P. albinus* were larger than those of *P. buddelundi*, they have a lower fecundity range (36.3 ± 13.8 egg) and fertility (19 ± 9 mancae). *P. albinus* also showed the lower mean reproductive allocation (9.94 ± 6.04) but the higher newborn body mass (1.44 ± 0.75 mg). Only *P. albinus* which has few offspring during each reproductive event often gives extensive parental care. This species with this type of high investment strategy uses much of its energy budget to care for its offspring.

Life history traits	***P. buddelundi***	***P. albinus***
Burrow digging	No	Yes
Body size and newborns mass		
Newborns body-mass (spring)	0.44 ± 0.21mg	1.44 ± 0.75 mg
Size of largest female	1.6 cm	2.4 cm
Body-mass of largest female	210 mg	–
Life span (estimated age)		
Largest female	18 months	24 months
Age at last reproduction	12 months	24 months
Itero/Semelparous	Iteroparous	Iteroparous
Breeding activity	March-May	March-June
	September-October	September
First reproduction		
Female size	0.65 cm	1.4 cm
Female body-mass	41.1 mg	129 mg
Female estimated age	3-3.5 months	9 months
Length of breeding period (first brood)	28-33 days	28-35 days
Fecundity (spring)	60.9 ± 3.5 eggs	36.3 ± 13.8 eggs
Fertility	53.13 ± 3.2 mancae	19 ± 9 mancae
Reproductive allocation (%)	29.06 ± 12.58	9.94 ± 6.04
Care of offspring	No	Yes
Offspring age estimated at the end of parental care	–	2 months

Table 3. Life history traits of the studied xeric species *Porcellio buddelundi* and *Porcellio albinus*.

All these results showed that *P. buddelundi* exhibited a set of characteristics corresponding to those of the r-strategists. In comparison, *P. albinus* displayed opposite trends that fit well with the expected characteristics of a k-strategist.

4. Behavioral strategies

The general objectives of our research are oriented, in this second part, toward understanding the behavioral mechanisms involved in the adaptation of terrestrial isopods to harsh desert conditions. The study model is *P. albinus*; It is found in habitats ranging from coastal sand nebkhas and up to desert ones, hundreds of kilometers away from the sea littoral. The choice of this model is justified by its unique burrowing behavior in the genus *Porcellio* in Tunisia. Based on the knowledge acquired in the terrestrial species model *H. reaumurii,* we propose to analyze the burrowing behavior and to identify the rhythm of activity of *P. albinus*, in order to understand the behavioral mechanisms of adaptations of this species to xeric conditions.

4.1. Spatial distribution of burrows

Among the desert-dwelling *Porcellio* species, widespread in southern Tunisia, only *Porcellio albinus* exhibits a burrowing behavior. *Porcellio albinus* shelters from the extreme heat and dryness of its desert habitat in a burrow. One wonders how this species “chooses” the location of its burrows in this type of habitat. What are the abiotic factors that influence this choice?

To answer these questions, several sampling campaigns were carried out in the Zarat station during 2013. The density of burrows, their spatial distribution, and their orientation were studied (see [23] for further details on material and methods). The species was also observed in the field. The analysis of the data collected showed that the distribution of the burrows depends on several factors. *Porcellio albinus* prefers to dig burrows at sandy nebkhas (the mean density of burrows per nebkha was 1.27 ± 1.64 burrows m^{-2}). This preference is justified by the nature of the soil that is easy to dig and the isopod’s low ability to do work on harder soils [23, 44]. It is also explained by the sand which has a low water retention capacity associated with a lack of capillarity between the dry surface and the moisture layers which further reduces the evaporation.

In each nebkha, the *P. albinus* burrows are located in a circular belt. In this belt, a preferred sector in which the burrows were grouped is oriented toward the southern direction, to avoid the prevailing wind direction E-NE at Zarat: *P. albinus,* leaving its burrow for forage stacks the sand torn from the burrow in front of the opening [44]. This sand, marked with the owner’s individual-specific chemical signature, is then used as a landmark to find the burrow after excursion [44]. Thus, to regain infallibly its burrow, *P. albinus* chooses, as the location of its burrows, a place sheltered from the prevailing wind.

In addition, *P. albinus* prefers to dig its burrow in nebkhas covered by a mixture of plants. Relating to this last factor, the high densities of burrows determined in nebkhas with a mixture of *Astragalus armatus* and *Stipagrostis pungens* indicate that these nebkhas could be considered as a high-quality micro-ecosystem for *P. albinus* [23].

4.2. Burrow morphology

For this study, five burrows located in nebkhas were randomly selected every month, from July 2012 to June 2013 in the sandy coastal area of Zarat, Gabès (in the southeast of Tunisia). For each burrow, three parameters were always determined: sand depth, angle between descending the neck of burrow and horizontal, and burrow length (**Figure 11**). To study the burrow morphology of *P. albinus*, the use of paraffin casting created an in situ, internal mold of the burrow structure. The cast is then excavated for analysis.

The results of this study showed that *P. albinus* is able to dig a burrow, in the habitat of Zarat, at any time of the year. All the burrows of *P. albinus* are dug toward the center of the nebkha; they were generally inclined and make an angle between descending neck of burrow and the horizontal ranging between 2 and 45°; the mean angle was about $22.2 \pm 12.87°$. Their depth ranged between 1 and 28 cm with a mean depth of 13.89 ± 9.43 cm. The total burrow length

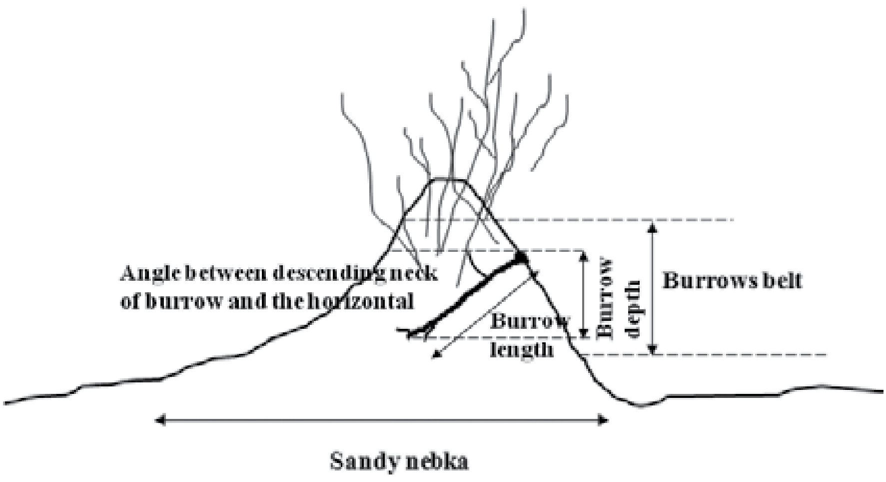

Figure 11. Parameters used to assess the morphology of the burrows.

Figure 12. Burrow with a single nesting chamber.

varied between 8 and 62 cm with an average burrow length of 24.04 ± 10.41 cm. The longest length of the burrow was reached in September, considered the hottest month of the year in Zarat area.

A total of 60 resin casts of the burrows of *P. albinus* were made in the coastal nebkha area of Zarat. The study of these casts showed that the burrows are either of simple form, a tunnel

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Figure 13. Burrow with two nesting chamber.

containing only one nesting chamber in its deep part (**Figure 12**), or of complex form, a tunnel containing two or more nesting chambers in its deep part (**Figure 13**); generally, in all casts studied, animals trapped in the cast were confined in the terminal part of the burrow.

4.3. Daily locomotor activity of *P. albinus*

Locomotor activity of *P. albinus*, deducted from monthly field observation data on the first and the last specimens in activity outside their burrows, was studied in synchrony con with light-dark cycle. During all the sampling period from November 2012 to October 2013, *P. albinus* showed a strict nocturnal activity: only individuals whose size is equal to or exceeds 8 mm began to emerge from their burrows after dusk and return to their shelters before dawn. This circadian rhythm of *P. albinus* is regulated by the rhythmic and natural variations of the duration of the dark period; a positive correlation is observed between the circadian period of the locomotor activity of the species and the duration of the scotophase ($r = 0.874$, $p \leq 0.05$).

5. Discussion

According to our results, among terrestrial isopods dwelling in xeric, semiarid, and arid habitats [75], the genus *Porcellio* with five species in Tunisia [76] ranks second after the genus *Hemilepistus* with nine species [50]. The *Porcellio* species discussed in this chapter showed a geographical distribution which depends on many ecological factors mainly climatic and orographic and of less importance edaphic. All of them were distributed south of the Tunisian Dorsal; the distribution of both xeric species *P. simulator* and *P. buddelundi* was limited, in the North, by the 500 mm isohyets. The distribution of *P. olivieri* was restricted to arid environments, while the rare species *P. albicornis* and *P. albinus* tolerate remarkably high temperatures and were able to reach the Sahara. Woodlice showing comparably effective adaptations to desert environments are *H. reaumurii* [26] and *Venezillo arizonicus* [77]. The latter two species possess protection against water loss through the cuticle which corresponds to a thicker and more calcified cuticle, thus reducing water evaporation in arid environments [53] and indicating that permeability to water has been reduced during adaptation to habitats with periodically or permanently low water availability. These physiological adaptations were, however, insufficient for coping with the harsh conditions of desert environments.

To survive in the harsh conditions of the desert and escape the danger of desiccation, the *Porcellio* survive the high temperature during the day in summer and autumn, either by vertically migrating (*P. buddelundi*, *P. simulator*, *P. olivieri*, and *P. albicornis*) or in a burrow which *P. albinus* dig in loose soil at any time of the year unlike *H. reaumurii* [26] who dig new burrows only in early spring. The maximum density of burrows, in nebkhas, was recorded in the southern sector to avoid the main wind direction [23]. *P. albinus* showed no daily activity; all year long it is a strictly nocturnal species. Individuals whose size is more than 8 mm started their activity after dusk to forage and return to their shelter before dawn. This nycthemeral rhythm of *P. albinus* is regulated by the rhythmic and natural variations of the duration of the scotophase. The circadian rhythm in *P. albinus* is probably generated by an internal clock that is synchronized to light-dark cycles and other cues in an organism's environment; this intrinsic timer was apparent in *Tylos europaeus* [78] and *H. reaumurii* [79, 80]. Nocturnal activity of *P. albinus* was correlated to a lower evaporation rate. In burrows, *P. albinus* breed and take care of their offspring for about 2 months [22]. Given the importance of a burrow for this species, the sand, scraped from the burrow and piled outside, when the member of a family started their activity, was used to close the burrow during the day probably as an antipredatory strategy. In addition, *P. albinus* used mechanisms similar to those found in *H. reaumurii* [55, 81], using combination of celestial mechanisms and the sand scraped from the burrow to relocate the burrows after foraging [44]. Burrows of *P. albinus*, in nebkhas of Zarat area, showed a simple or complex tunnel with one nesting chamber in its deep part for the first and with two nesting chamber for the second. *P. albinus'* burrow length reached its maximum in September.

In addition to behavioral adaptations, the pre-desert and desert species of *Porcellio* have developed reproductive strategies that allow them to better succeed in the colonization of arid environments. The study of the reproductive phenology of the populations of the two *Porcellio* species from pre-desert ecosystems in Tunisia allowed to bring new fundamental knowledge on the dynamics of these populations as well as on the reproductive traits of the xeric *Porcellio* species *P. albinus* and *P. buddelundi*. The reproduction of these two iteroparous *Porcellio* was characterized by two breeding seasons: the most important one in spring and the other in autumn distinctly separated by a sexual rest phase [22, 24]. This reproductive phenology differs from that of (1) mesic species such as *P. variabilis* [33, 82], which generally shows a breeding period spread over several months followed by a sexual rest and (2)

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H. reaumurii and other desert species from the Middle East characterized by a single spring or autumn breeding season [45, 72, 83]. Our results about reproductive traits of both species showed that *P. buddelundi* exhibited a set of characteristics corresponding to those of the r-strategists: a shorter life span, a smaller size, early sexual maturity, higher fertility, and a reproductive allocation to maximize brood size. In comparison, *P. albinus* displayed opposite trends to which parental care was added which corresponds well to expected characteristics of a k-strategist. These results reinforce the Sutton et al. [25] observations and those of Quadros et al. [74] by showing that *P. buddelundi* and *P. albinus* have opposite life history traits that correspond to their degree of habitat specialization: the steneodynamic species corresponds to a K-selected habitat specialist and the eurydynamic species to an r-selected habitat generalist. According to the study of life history traits of the two species, *P. albinus* with its capacity to dig burrows displays a fairly developed social behavior compared to other species of the genus which allowed him to be the most advanced of the *Porcellio* genus but remain less evolved than *H. reaumurii*.

The quite diverse *Porcellio* genus in arid regions is an integral part of pre-desert macro-arthropod communities. In a single square meter of soil of desert ecosystems, as many as four species of *Porcellio* may be collected [76]. Under comparable conditions where earthworms are absent, ant communities may comprise up to 28 species [84]. All of these *Porcellio* species as many other terrestrial isopods [7, 13–15, 17], termites, and ants contribute to the consumption and mineralization of a significant part of litter (litter transformers) in arid areas [1, 16, 85]; they build holorganic structures (their fecal pellets) that serve as incubators for microbial activities [Lavelle, 1996]. The burrowing and digging activity of *P. albinus* as well as the vertical migration of the other pre-desert species of the genus *Porcellio* may influence the infiltration properties of the soil and, thus, on the whole process of water movement within the soil profile and on the subsurface flow process. This was studied in the genus *Hemilepistus* from arid region of southeastern Russia, at an estimated population density of 1.4 million individuals ha^{-1}; the animals were deemed capable of transporting, from a depth of up to 1 m to the surface, 5–6 tonnes of soil, of a different granulometrical and chemical composition, annually [86]. Macroporosity related to the activity of other arthropod groups such as ants and termites demonstrated prodigious earth-moving abilities, which may contribute importantly to soil formation. For example, in the Chihuahuan desert, four species of ants which have relatively short-lived colonies transported between 21 and 86 kg ha^{-1} $yr.^{-1}$ of subsurface soil to the surface, and some species of termites produce erodible surface galleries different in composition from the surface soil [16]. As result of "ecosystem engineers'" work, topsoil was improved and was able to support a more diverse and dense vegetation.

6. Future prospects

Future prospects, which could be considered from our research and have led to the following questions, are as follows:

- The reproductive phenology of desert *Porcellio* species other than *P. buddelundi* and *P. albinus*, such as *P. olivieri* and *P. simulator*, and their reproductive strategies.

- The behavioral aspect of reproduction in pre-desert and desert species from arid environments: the choice of the sexual partner, sexual conflicts, polygamy, parental care, etc.
- Physiological and genetic mechanisms that facilitate the survival and therefore the reproduction of these species in these desert habitats.
- Social behavior of *P. albinus* (recognition systems of offspring, different members of the same family, volatile or nonvolatile discriminators) is one of the priorities of our future research to better understand the physiological mechanism that allowed its adaptation and prosperity in the difficult conditions that prevail for several months of the year in its range.

The susceptibility of *P. albinus* to temperature rise and moisture decline makes this terrestrial isopod an appropriate biological model for examining its potential responses to climate change. This line of research could be considered in the context of global climate change such as the study in microcosms of the effects of changes in temperature and relative humidity on the activity, aggregation, and survival of *P. albinus*.

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Chapter 4

Ecological and Environmental Assessment of Nara Desert Wetland Complex (NDWC), Khairpur, Sindh-Pakistan

Muhammad Saleem Chang

Additional information is available at the end of the chapter

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Abstract

The Nara Desert Wetland Complex (NDWC) includes sandy dunes, steep hills and occupies low lying flat zones associated with different natural wetlands formed from the seepage of Nara Canal. These different wetlands are the major perennial source of water to the agricultural lands, local communities, wildlife and for grazing livestock. The NDWC encompasses more than 225 seasonal and permanent small, medium and large sized lakes/wetlands. The total area of Nara Canal is distributed about (108,960 hectares) which starts from Sorah to Head Jamrao. The NDWC was declared in 1972 as a Game Reserve area for the protection of wild animals. The NDWC is also recognized an important potential Ramsar Site. The different floral habitation in the Nara Desert consists of mostly drought resistant vegetation of phytoplankton, reed vegetation, herbs, shrubs and trees. The area is ecologically rich with the faunal biodiversity that includes zooplankton, invertebrates, fishes, amphibians, reptiles, birds, and small and large mammals. The NDWC has received high values for its economic, social, floral and faunal habitat, aquatic biodiversity since the local communities are directly or indirectly dependent on these natural sustainable resources. During the sampling of environmental parameters, most of the wetlands were determined to be seasonal and permanent freshwater, brackish and hypersaline lakes.

Keywords: Nara Desert wetland complex, Nara Canal, biodiversity, ecologically-sustainable resources, environmental parameters

1. Introduction

1.1. Nara Desert wetland complex (NDWC)

The Nara Desert Wildlife Sanctuary is located between 26°28° N and 68°70° N (Elevation 50–115 m) in the province of Sindh, Pakistan. The desert area is approximately 23,000 km^2 semiarid, receiving most of its water 88–135 mm of annual rainfall sporadically during the season of monsoon. These wetlands have rich variety of floral and faunal life such, as various aquatic plant species and different animal species of fishes, amphibians, reptiles, birds and mammals. However, the region is of diverse ecological value for the biodiversity of plant and animal species. These wetlands are distributed in different districts which usually start from Ghotki, Sukkur, Khairpur and ends in Sanghar District [1–4]. In the Nara Canal region, the ground water level usually varies around 76 mm. The capacity of recharging these wetlands in the region is very low due to low rainfall. The level of water table varies between 2.5 and 5 m. In the nearest lands to the Nara Canal, the water level increases up to 10–18 m. Most of the wetlands were developed from sand dunes while a few were developed by deposition of silt [5]. Irrigation system on Nara Canal is contained from upper Nara between Sukkur Barrage to the south Jamrao Headwaters and includes major canals such as Jamarao, Mithrao, Khipro and Thar [1–6]. The area is geographically part of the Indus Basin and is composed of alluvial sediments which are deposited by previous and current different branches of the rivers. The sediments of the area are carried by Indus River which have tertiary shale and limestone basement. The sediments are composed of acolin sands that have previously been deposited during the Pleistocene Epoch. The composition of soil is from sandy to loamy and some part of soil is scarcely made up with the loamy sands. The color of soils is generally from brown to gray brown with the 5–15% mixture of $CaCO_3$. The soil is usually composed of nan-saline, non-sodic mixed with poor organic materials having range of pH from 7.8 to 8.4. The developing hypersaline wetlands are common due to the overflow from Nara Canal [5]. The region is distributed with the sandy and steep hills which are locally famous as "patt", "Tars" or "Tals". The main source of water for the agriculture and other activities is Nara Canal which extends up to 4–5 km from both sides of canal [5] (**Figure 1**).

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Figure 1. Map of study area of Nara Desert wild life sanctuary.

The area has high wind velocity with the huge amounts of shifting of sand hills and have high temperature with higher soil radiation in the summer and observed very short rainfall and high evapo-transpiration. In the Nara Desert the average minimum temperature is 20°C and the maximum temperature is 45°C. In the summer, the hottest months are from May to July, when the temperature increases from 45 to 51°C. In the winter season, the lower temperature ranges from 20 to 28°C for the months of December to January. In the region, the annual rainfall from 88 to 135 mm occurs during the months from July to September [1–4, 6]. The region of NDWC includes about more than 225 small to medium and some large sized-wetlands; some of these are seasonal and most are permanent. The Nara Canal is the largest canal of Sindh Province and covers more than 108 million hectares. On the both sides of Nara Canal the area is covered with woodland, riverine forest, scrub and desert scrubs. In the region, the source of water for wetlands is the seepage from the Nara Canal [1–4, 7].

The climate of the area is mainly arid having high temperatures and late summer rains observed. The seasonal rainfall is varied and is less than 250–300 mm and rainy season usually starts from June to September. Before the monsoon season, the average temperature is exceeding 45°C in the desert region and in the plains of NDWS the average temperature between 30 and 40°C. The wetland complex is recognized of great hydrological values as 98% Nara Canal water is used for agriculture and only 2% water is used for domestic and drinking purposes. The wetland complex of Nara Canal is 361.6 km long and 90–135 m wide. The maximum water depth of wetland complex is 7.5 m. The highest water discharges of Nara Canal are reported in the months of May–July and the minimum water flow in the August [1, 2, 5].

1.2. Socio-economic status of area

According to the census survey report of 2016, the total population of Nara Taluka is counted 160,985. The target area of Nara Taluka the total population can be estimated to be more than

60,000. The major communities are living in the area study are Baradin, Baloch, Chang, Shard, Syed, Rapper, Dashi, Maleah, Khaskheli, Channa, Sahta, Gopang, Bhurgari, Rind, Nizamani, Mirbahar, Khoso, Wassan, Deewan, Ibupoto, Kakepoto, Rajar, Mirani, and Macchi. From these communities, a few numbers of people are engaged in artisan work, trade, business and job in government departments etc. The Livestock and agriculture are the major source of income of local communities. Cotton and wheat are the main crops cultivated in the Nara while sugarcane, barely, oil seed, pulses, vegetable and fodder are also cultivated. The peoples of the area are living in the worst condition and they have least health facilities, drinking water, education and they do not have available basic life facilities. In spite of low productivity of area, the desert area sustains relatively higher human (1.05 m) and livestock (1.25 m) populations was reported, respectively. The livestock is the major source of income, meat and wool in the area. The overexploitation of vegetation by the grazing animals and the cutting of trees and shrubs for fuel purposes have resulted in environmental degradation that threatens the natural resources in this area. There is no developed transportation system in the Nara Desert. Due to low literacy rate in the area, there is a lack of employment opportunities [5].

1.3. Floristical and faunilistical assessment of Nara Desert wetland complex

In the region of NDWC the richest biodiversity comprises a mosaic habitat of sandy hills, canals, forests, agriculture fields, freshwater and hypersaline wetlands. The area has the richest plant biodiversity consisting of 160 plant species belonging to 118 genera and 45 families were recorded [8–10]. The seasonal crops include sugarcane, cotton, wheat, barley and sunflower. The major vegetation in the sandy habitats are *Prosopis cineraria*, *Acacia niloticus*, *Salvadora oleoides*, *Dalbergia sissoo*, *Tamarix aphylla*, *Melia azedarach*, *Populus spp*. and *Calotropis procera* [5, 6, 11–13]. In the Nara Desert, the various drought-tolerant plant species, such as cactuses and succulents (*Agaves spp*.), *Aerva javanica*, *Calligonum polygonoides*, *Crotalaria burhia*, *Capparis decidua*, *Dipterygium glaucum*, *Tephrosia villosa*, *Aristida adscensionis*, *Cassia*, *Tephrosia uniflora* and *Cassia italic* were recorded [5]. In the zone of Nara Desert, a mixed vegetation of shrubs and plants, such as *Typha spp*., *Hydrilla verticillata*, *Paspalum distichum*, *Polygonum hyaropier*, *Urticularia lotus*, *Nelumbium nuciferum*, *Desmostachya bininata*, *Phragmites karka*, *Saccharum bengalensis* and *Tamarix indica* were also reported [5, 8–10, 14–23].

The region has been received the high socio-economic values for the local community which is dependent on the agriculture, livestock, fish farms and freshwater wetlands. In this area, the small to medium villages are scattered and their major economies are agriculture and livestock [1, 2, 5, 17, 24]. In this zone, the variety of different wild mammalian species includes *Hemiechnus auritus*, *Caracal caracal*, *Felis chaus*, *Felis margarita*, *Herpestes edwardsi*, *Herpestes javanicus*, *Canis lupus pallipes*, *Vulpes zerda*, *Hyaena hyaena*, *Mellivora capensis*, *Manis crassicaudata*, *Gazella bennettii*, *Hyelaphus porcinus*, *Sus scrofa cristatus*, *Lepus tibetanus*, *Funambulus pennantii*, *Hystrix indica*, *Lutrogale perspicilletta*, *Lutra lutra* and *Prionailurus viverrinus* [5, 25–27]. The NDWC has the richest biodiversity of native and migratory avian fauna of which more than 78 avian species were recorded [5, 7, 24, 25, 28–30]. From this region, two threatened species of Indian-backed vulture and houbara bustard were recorded. The indigenous bird species of myna, crow, sparrow, red-wattled lapwing, white-tailed plover, and stilt were commonly observed. Two bird species of large-pied wagtail (*Motacilla maderaspatensis*) and rock bunting (*Emberiza cia*) were the first time reported in this region [5]. Some important bird species categorized by International Union for Conservation of Nature (IUNCN) Red List as Least Concern species include the Indian darter, black or red-naped ibis, ruddy Shel duck; as Vulnerable, the marbled teal, and as Near Threatened, the ferruginous duck [5, 23, 24, 28–32].

2. Material and methods

For the collection of data the study was carried out in Nara Desert Wildlife Sanctuary which is located between 26°28° N and 68°70° N (Elevation 50–115 m) in the province of Sindh, Pakistan For the collection of flora species, the direct method/observation was applied during the diurnal period. To collect the faunal species, the direct and indirect methods were applied. For the collection of important ecological data of floristical and faunistical species, the field work for diurnal and nocturnal surveys were conducted randomly.

For the various physicochemical parameters, water from 10 randomly selected stations from a few selected lakes of NDWC were sampled monthly from January to December 2015. The samples were collected from two different sampling sites of upper surface and lower bottom layers and were kept in (Van Dorn Plastic Bottles 1.5 liter) during the collection period.

Parameters	Abbreviation	Units	Procedure
Temperature	Temp	°C	Mercury thermometer
pH	pH	pH Unit	pH meter
Electrical conductivity	EC	Mu/Scm	Conductivity meter
Total dissolved solids	TDS	mg L^{-1}	WTW 320
Turbidity	Turb	NTU	Nephlometric turbidity meter
Calcium	Ca	mg L^{-1}	Titration method (EDTA)
Magnesium	Mg	mg L^{-1}	Titration method (EDTA)
Hardness	Hard	mg L^{-1}	Titration (silver nitrate)
Carbonate	HCO	ppm	Titration (2310)
Bi-carbonate	HCO_3	ppm	Titration (2310)
Alkalinity	Alkal	mg L^{-1}	Titration (silver nitrate)
Chlorides	Cl	mg L^{-1}	Titration (silver nitrate)
Sodium	Na	mg L^{-1}	WTW (320)
Potassium	K	mg L^{-1}	Titration method (EDTA)
Sulphate	SO_4	mg L^{-1}	Titration (2310)
Biological oxygen Demand	BOD	mg L^{-1}	Winkler method
Dissolved oxygen	DO	mg L^{-1}	Winkler method

Table 1. Analytical procedure for physicochemical parameters of NDWC during 2015.

After the samples were kept in 10% nitric acid for 24 hours and rinsed with the distilled water. Water samples were mixed in acid-washed container, rinsed with distilled water, and then stored at 4°C for further analysis. For quality assurance, the samples were analyzed in duplicate through careful standardization and samples examined. Physicochemical analysis was performed by the standardized methods [33]. Chemical properties of water samples including water temperature, depth, and transparency were measured with the Secchi Disk. The temperature was measured by a mercury thermometer immersed into a water depth of 15 cm for 2–5 mins. The pH was measured by of an Orion Model 420 pH meter. The EC, TDS, and Na parameters were measured by a WTW 320 conductivity meter. Alkalinity, hardness, Cl and phosphate were analyses conducted by the standardized methods as recognized by WHO [34]. Titration method (2310) was used to measure Ca, HCO_3 and HCO. Mg and K were analyzed by spectrometry. For the analysis of BOD and DO, the Winkler method and a Jenway Model 9071 Oxygen Meter were used, respectively (**Table 1**).

3. Results

3.1. Ecological assessment: (Flora and Fauna)

Flora: In the region of Nara Desert a variety of different floral species of aquatic as well as terrestrial plants, herbs, shrubs and drought resistant plant species were recorded (**Table 2**).

S. No#	Scientific Name	Common Name	Local Name
1.	*Acacia nilotica*	Thorn mimosa, Bubul	Bubar
2.	*Dalbergia sissoo roxb*	Sisu, Tali	Talehi
3.	*Alhagi maurorum*	Camel-thorn bush	Kandero
4.	*Albizia durraz*	Siris	Sareenhn
5.	*Mimosa pudica L.*	Chui-mui, Lajwanti	Sharam Booti
6.	*Prosopis juliflora*	Mosquite	Deevi
7.	*Prosopis cinreria*	Jamal gotha	Kandi
8.	*Tamarind indica linn*	Imli	Gidaamri
9.	*Trigodela L.*	Proshan, kakpie	Hurbo
10.	*Ocimum L.*	Basil	Nazbu
11.	*Grevia L.*	Phalsa	Pharva
12.	*Azadirachia indica*	Neem	Nim
13.	*Ficus benghalensis L.*	Banyan tree	Barr
14.	*Ficus religiosa L.*	Sacred Fig	Pipal
15.	*Morus alba L.*	White Mulberry	Toot
16.	*Eucalyptus camaldulensis*	Red Gum, Eucalyptus	Safedo
17.	*Zizephus mauritiana Lam*	Berry	Baer

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S. No#	Scientific Name	Common Name	Local Name
18.	*Salvadora persica L.*	Peelu	Khabbar
19.	*Cordia gharaf*	Gondni	Gaiduri
20.	*Tamarix passerinoides*	Tamarisk	Layee
21.	*Pennisatum glaicum L.*	Bajra	Bajhari
22.	*Zea mays L.*	Corn	Makai
23.	*Desmostachya bipinnata*	Dub, Halfa grass	Drubh
24.	*Calotropis procera*	Milk Weed	Akk
25.	*Eruka sativa*	Salad Rocket	Janmbho
26.	*Opentia ficus indica L.*	Cactus	Thohar
27.	*Capparix decidus*	Kapparis	Kirar
28.	*Suaeda fruiticosa*	Shrubby Seablight	Laani
29.	*Citrullus colocynchis L.*	Bitter Apple	Tooh
30.	*Calligonum polygonoides*	Phog	Phog
31.	*Aerva javanica*	Kopak Bush	Booh
31.	*Tamarix aphylla*	Tamarisk	Lao
32.	*Salvadora oleoides*	Jaal	Jaar
33.	*Crotolaria burhia*	Burhia Rattlepod	Soma
34.	*Dipterygium glaucum*	Safrawi	Phair
35.	*Aristida adscensionis*	Sixweeks Threeawn	Lumb Gaah
36.	*Cassia italic*	Cassia, Golden tree	Ghora wal
37.	*Tephrotia uniflora*	Senegal	Siringh/Andhari
38.	*Teophrotia villosa*	Creeping Thistle	Phoodno
39.	*Typha latifolia*	Cattail	Kanahn
40.	*Typha angusta*	Cattail	Kaani
41.	*Paspalum distichum*	Knotgrass	Naru Gaah
42.	*Hydrilla verticillata*	Hydrilla	Hydrilla
43.	*Nyphaea lotus*	White Lotus	Kanwal
44.	*Polygonum hyaropier*	Blake's Knotweed	Anjbar
45.	*Urticulara lotus*	Water Lotus	Kanwal
46.	*Nelumbium nuciferum*	Nelumbium	Kanwal

Table 2. Flora of NDWS.

Fauna: Amphibians: In the Nara Desert three amphibian species belonging from two families of Ranidae and Bufonidae were reported (**Table 3**).

Reptiles: Region of Nara Desert is considered rich in herpeto-fauna with 24 reptilian species belonging to three orders and 12 families. Out of the 24-reptilian species, 2 were herbivores,

S. No#	Scientific Name	Common Name
1.	*Crocodylus palustris*	Mugger crocodile
2.	*Kuchuga tecta*	Saw-back turtle
3.	*Kuchuga smithi*	Brown turtle
4.	*Geoclemys hemiltonii*	Spotted-pond turtle
5.	*Canis aureus*	Asiatic jackal
6.	*Fellis chaus*	Jungle cat
7.	*Prionailurus viverrinus*	Fishing cat
8.	*Felis silvestris*	Desert cat
9.	*Vulpes vulpes*	Red fox
10.	*Lutrogale perspicillata*	Smooth-coated otter
11.	*Herpestes javanicus*	Small Indian mongoose
12.	*Herpestes edwardsi*	Gray mongoose
13.	*Axis porcinus*	Hog deer
14.	*Sus scrofa*	Indian wild boar
15.	*Funambulus pennanti*	Palm squirrel
16.	*Gerbilus nanus*	Balochistan gerbill
17.	*Hemiechinus collaris*	Long-eared hedgehog
18.	*Hystrix indica*	Indian crested porcupine
19.	*Lepus nigricollis*	Desert hare
20.	*Meriones hurrianae*	Indian desert jird
21.	*Mus musculus*	House mouse
22.	*Tatera indica*	Indian gerbil
23.	*Aspiderestes gangeticus*	Indian soft shell turtle
24.	*Lissemys punctate punctata*	Indian flapshell turtle
25.	*Naja naja naja*	Indian cobra
26.	*Echis carinatus*	Saw-scaled viper
27.	*Eryx johni*	Indian sand boa
28.	*Lytorhynchus paradoxus*	Sindh awlheaded sand snake
29.	*Platyceps rhodorchis*	Cliff racer platyceps
30.	*Platyceps ventromaculatus*	Glossy-bellied racer
31.	*Xenochrophid piscator*	Checkered keelback
31.	*Calotes versicolor*	Tree lizard
32.	*Trapelus megalonyx*	Afghan ground agama
33.	*Hemidactylus brookii*	Yellow-bellied house gecko
34.	*Hemidactylus brooki*	Spotted Indian house gecko
35.	*Cyrtopodion scaber*	Keeled rock gecko

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S. No#	Scientific Name	Common Name
36.	*Ophoimorus raithmai*	Three-fingered sand-fish
37.	*Ophoimorus tridactylus*	Indian sand swimmer
38.	*Eutrophis macularia*	Bronze grass skink
39.	*Varanus bengalensis*	Bengal monitor
40.	*Varanus griseus*	Desert monitor
41.	*Acanthodactylus cantoris*	Indian fringetoed sandy lizard
42.	*Bufo stomaticus*	Marbled toad
43.	*Hoplobatrachus tigerinus*	Bull frog
44.	*Rana cyanophlyctis*	Skittering frog
45.	*Tachybaptus ruficollis*	Little grebe
46.	*Podiceps nigricollis*	Black-necked grebe
47.	*Phalacrocorax niger*	Little cormorant
48.	*Phalacrocorax carbo*	Large cormorant
49.	*Phalacrocorax fuscicollis*	Indian darter
50.	*Ardea cinerea*	Gray heron
51.	*Ardea purpurea*	Purple heron
52.	*Ardeola grayii*	Indian pond heron
53.	*Bubulcus ibis*	Cattle egret
54.	*Egretta alba*	Large egret
55.	*Egretta intermedia*	Intermediate egret
56.	*Egretta garzetta*	Little egret
57.	*Egretta gularis*	Reef heron
58.	*Ixobrychus minutus*	Little bittern
59.	*Ixobrychus sinensis*	Yellow bittern
60.	*Tadorna ferruginea*	Ruddy shelduck
61.	*Marmaronetta angustirostris*	Marbled teal
62.	*Anas crecca*	Common teal
63.	*Anas platyrhynchos*	Mallard
64.	*Anas strepera*	Gadwall
65.	*Anas clypeata*	Shoveller
66.	*Aythya ferina*	Common pochard
67.	*Aythya nyroca*	Ferruginous duck
68.	*Aythya fuligula*	Tufted duck
69.	*Aythya collaris*	Ring-necked duck
70.	*Elanus caeruleus*	Blackwinged kite
71.	*Milvus migrans*	Common kite

S. No#	Scientific Name	Common Name
72.	*Haliastur indus*	Brahminy kite
73.	*Accipiter badius*	Central Asian shikra
74.	*Butastur teesa*	White-eyed buzzard
75.	*Circus aeruginosus*	Marsh harrier
76.	*Falco tinnunculus*	Common kestrel
77.	*Pandion haliaetus*	Osprey
78.	*Francolinus pondicerianus*	Gray partridge
79.	*Francolinus francolinus*	Black partridge
80.	*Amaurornis phoenicurus*	White-breasted waterhen
81.	*Gallinula chloropus*	Indian moorhen
82.	*Porphyrio porphyrio*	Purple moorhen
83.	*Fulica atra*	Common coot
84.	*Charadrius leschenaultia*	Greater sand plover
85.	*Vanellus indicus*	Redwattled lapwing
86.	*Vanellus leucurus*	White tailed plover
87.	*Charadrius dubius*	Little ringed plover
88.	*Charadrius alexadrinus*	Kentish plover
89.	*Charadrius mongolus*	Lesser sand plover
90.	*Numenius arquata*	Curlew
91.	*Numenius phaeopus*	Whimbler
92.	*Limosa lapponica*	Bartailed godwit
93.	*Tringa totanus*	Common redshank
94.	*Tringa stagnatilis*	Marsh sandpiper
95.	*Tringa nebularia*	Green shank
96.	*Tringa glareola*	Wood sandpiper
97.	*Tringa hypoleucos*	Common sandpiper
98.	*Gallinnago gallinago*	Common snipe
99.	*Calidris minutus*	Little stint
100.	*Calidris alpine*	Dunlin
101.	*Philomachus pugnax*	Ruff
102.	*Himantopus himantopus*	Blackwinged stilt
103.	*Larus heuglini*	Heuglin's gull
104.	*Larus brunnicephalus*	Brown headed gull
105.	*Larus ridibundus*	Black Headed gull
106.	*Larus genei*	Slenderbilled gull
107.	*Gelochelidon nlitica*	Gull-billed tern

S. No#	Scientific Name	Common Name
108.	*Hydroprogne caspia*	Caspian tern
109.	*Sterna aurantia*	Indian River tern
110.	*Sterna acuticauda*	Blackbellied tern
111.	*Sterna albifrons*	Little tern
112.	*Sterna sendvicensis*	Sandwitch tern
113.	*Columba livia*	Blue rock pigeon
114.	*Streptopelia decaocto*	Ring dove
115.	*Sterptopelia senegalensis*	Little brown dove
116.	*Centropus sinensis*	Crown pheasant
117.	*Ketupa zeylonensis*	Brown fish owl
118.	*Athene brama*	Spotted owlet
119.	*Ceryle rudis*	Pied kingfisher
120.	*Alcedo athis*	Common kingfisher
121.	*Halcyon smyrnensis*	Whitebreasted kingfisher
122.	*Merops orientalis*	Green-bee eater
123.	*Merops persicus*	Blue-cheeked bee eater
124.	*Corcias benghalensis*	Indian roller
125.	*Upupa epops*	Common hoopoe
126.	*Amomanes deserti*	Desert lark
127.	*Calendrella brachydactyla*	Great short-toed lark
128.	*Galerida cristata*	Crested lark
129.	*Riparia diluta*	Pale sand martin
130.	*Hirundo fuligula*	Crag/rock martin
131.	*Hirundo rustica*	Barn or common swallow
132.	*Lanius isabellinus*	Rufous tailed or Isabelline shrike
133.	*Lanus meridionalis*	Southern gray shrike
134.	*Lanius vittatus*	Bay backed shrike
135.	*Dicrurus adsimilis*	Black drongo
136.	*Acridotheres adsimilis*	Indian myna
137.	*Sturnus vulgaris*	Common
138.	*Phoenicurus ochruros*	Starling
139.	*Oenanthe albonigra*	Hume's wheatear
140.	*Saxicoloides fulicata*	Indian robin
141.	*Saxicola caprata*	Pied robin chat
142.	*Oenanthe isabellina*	Isabelline wheatear
143.	*Oenanthe sdeserti*	Desert wheatear

S. No#	Scientific Name	Common Name
144.	*Corvus splendens*	House crow
145.	*Dendrocitta vagabunda*	Tree pie
146.	*Prinia flaviventris*	Yellow bellied prinia
147.	*Prinia burnesii*	Rufous vented prinia
148.	*Pycnonotus leucogenys*	White-cheeked bulbul
149.	*Pycnonotus cafer*	Red-vented bulbul
150.	*Turdoides caudatus*	Common babbler
151.	*Turdoides earlie*	Striated babbler
152.	*Turdoides striata*	Jungle babbler
153.	*Rhipidura aureola*	White browed fantail
154.	*Phylloscopus collybita*	Common chiffchaff
155.	*Acrocephalous stentoreus*	Clamorous reed warbler
156.	*Sylvia curruca*	Lesser whitethroat sylvia
157.	*Phylloscopus trochiloides*	Greenish warbler
158.	*Motacilla alba*	White wagtail
159.	*Motacilla flava*	Yellow wagtail
160.	*Nectarinia asiatica*	Purple sunbird
161.	*Passer domesticus*	House sparrow
162.	*Passer pyrrhonotus*	Sindh jungle sparrow

Table 3. Fauna of NDWS.

13 were carnivores and 9 were insectivores. A famous indigenous Vulnerable reptilian species of marsh crocodile (*Crocodylus palustris*) was also reported from the Nara Canal and its adjacent territories (**Figure 2**) (**Table 3**).

Birds: In the region of NDWC, these wetlands are recognized as the major habitats for the variety of rare and endangered migratory birds. In NDWC, 118 bird species belonging to 13 orders and 35 families belonging were reported. Fifty-nine birds were native species while 53 birds were migratory species. The important migratory birds were the marbled teal, *Anan angustirostris* (Vulnerable-threatened) and the ferruginous duck, *Aythya nyroca* and the Indian darter, *Anhyinga rufa* (Near-threatened) (**Table 3**).

Small mammals: From the habitat of NDWC the small mammal populations belonging to 3 orders and 5 families were also reported. The small mammals included 5 granivores, 2 herbivores and 1 omnivore (**Table 3**).

Large Mammals: Large Mammals: Twenty-five species of large mammals were reported. From order Carnivora, 10 species included the jungle cat, jackal, small Indian mongoose, gray mongoose, wolf and red fox and from the Order Artiodactyla, the wild boar (**Table 3**) (**Figure 3–6**).

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Figure 2. A view of marsh crocodile.

Figure 3. A view of Lake in NDWC.

Figure 4. A view of plantation in NDWC.

Figure 5. A view of Desert dune in NDWC.

Figure 6. A view of Typha in NDWC.

3.2. Analysis of physicochemical parameters

The highest air temperature of 45°C was measured in July and the lowest of 20°C was measured in January (**Tables 4**, **11**). The highest and lowest water temperatures were 42 and 17°C, respectively (**Table 4**). The highest and lowest values (9.3 and 6.9) for pH were measured in November and December, respectively (**Tables 11**, **12**). The highest and lowest values (9120 and 364 mu/Scm) for EC were measured in November and May, respectively (**Tables 11**, **13**). The highest and lowest values (1042 and 214 mg/L) for TDS were measured in March and May, respectively (**Tables 7**, **13**). The highest and lowest values (186 and 0.20 NTU) for turbidity were measured in the months of January – September, respectively (**Tables 7**, **9**). The highest and lowest values (1214 and 6 mg/L) for Ca were measured in January and November, respectively (**Tables 8**, **10**). The highest and lowest values (876 and 12 mg/L) for Mg were measured in March and May, respectively (**Tables 8**, **13**). The highest and lowest values (5536 and 140 mg/L) for hardness were measured in March and May, respectively (**Tables 7**, **13**). The

Parameters	**Months**											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Temp: Air	20	25	28	32	38	43	**45**	42	32	28	23	20
Tem: Water	17	21	23	28	29	38	33	37	29	24	20	17
pH	8.2	8.1	8.3	8.2	8.0	7.9	7.9	8.0	7.8	7.9	8.0	8.1
EC	985	915	954	885	875	870	850	860	820	890	970	930
TDS	630	618	613	605	590	598	600	620	580	612	640	624
Turb	30	35	32	38	40	42	45	37	28	33	35	41
Ca	40	38	52	50	58	52	65	54	35	34	45	42
Mg	27	30	37	32	35	33	40	25	23	29	24	38
Hard	210	234	270	218	245	240	256	228	205	215	225	220
Alkal	3.5	3.7	3.8	3.9	3.4	3.7	4.0	3.8	3.2	3.5	3.6	3.7
Cl	131	127	122	132	115	142	145	130	120	124	140	135
Na	128	143	145	135	120	128	150	132	110	122	130	137
K	18	20	21	23	19	20	25	21	16	17	20	18
SO_4	128	138	140	98	32	110	116	114	105	118	120	132
HCO	—	—	—	—	—	—	—	—	—	—	—	—
HCO_3	175	152	162	147	150	134	130	170	140	153	165	160
BOD	3.0	3.5	3.2	3.0	2.9	3.3	2.8	3.1	3.5	3.4	3.8	3.7
DO	4.8	4.5	4.9	4.2	**3.7**	4.0	3.9	4.3	4.2	4.6	4.1	4.7

Table 4. Physicochemical analysis of water sample of station 1. Gunjo Bhanbharo Lake.

Parameters	**Months**											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Temp: Air	20	25	26	30	32	37	42	38	32	27	23	20
Tem: Water	16	21	23	26	29	33	38	35	29	24	20	17
pH	8.2	8.0	8.1	7.9	8.0	7.7	7.8	8.1	7.6	8.0	7.9	8.2
EC	2860	2478	2730	2380	2595	2517	2370	2678	2173	2594	2436	2247
TDS	1830	1800	16,500	1700	1540	1460	1285	1678	1240	1315	1464	1780
Turb	33	24	30	22	25	19	21	20	18	26	28	29
Ca	140	137	150	145	130	142	120	126	114	118	132	122
Mg	60	48	75	70	52	65	45	44	42	58	53	66
Hard	600	652	680	575	580	638	590	618	563	598	620	640
Alkal	7.0	8.2	12.0	9.1	8.0	8.5	10.0	7.8	6.0	11.0	9.0	8.4
Cl	192	185	210	190	170	192	165	204	154	167	184	180

Parameters	Months											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Na	382	370	350	308	315	338	286	268	250	317	375	347
K	32	36	38	32	28	25	24	33	20	24	27	23
SO_4	778	754	725	674	635	653	605	725	582	762	683	697
HCO	—	—	—	—	—	—	—	—	—	—	—	—
HCO_3	350	270	285	315	260	290	250	305	250	360	376	326
BOD	3.5	3.4	3.2	3.6	3.6	3.7	3.8	3.5	3.7	3.3	3.8	3.4
DO	5.0	4.9	4.8	4..7	4.9	4.5	4.8	4.8	4.6	4.3	4.2	4.7

Table 5. Physicochemical analysis of water sample of station 2. Bachal Bhanbharo Lake.

Parameters	Months											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Temp: Air	21	24	26	30	32	37	43	36	32	27	23	20
Tem: Water	18	20	23	28	29	34	39	32	29	24	20	17
pH	8.0	7.9	7.6	7.7	7.8	7.6	7.5	7.8	7.3	7.5	7.9	7.7
EC	925	876	856	815	814	764	725	780	705	802	883	865
TDS	586	562	547	540	510	487	462	516	443	550	532	580
Turb	9.2	11.4	11.9	10.7	10.4	11.9	12.3	10.9	11.2	11.0	11.6	10.8
Ca	82	74	68	80	54	67	45	56	40	65	75	70
Mg	74	70	62	51	52	58	48	66	42	54	68	62
Hard	538	518	426	487	410	468	430	500	410	485	520	508
Alkal	3.5	3.2	2.6	2.8	2.5	2.9	2.2	2.8	2.1	3.1	3.2	3.4
Cl	168	156	139	141	130	127	118	1162	106	149	156	150
Na	42	33	38	41	34	35	32	36	27	40	38	39
K	40	34	32	29	30	35	34	47	28	37	36	33
SO_4	208	193	195	165	173	182	164	158	153	168	192	187
HCO	—	—	—	—	—	—	—	—	—	—	—	—
HCO_3	142	137	130	129	123	132	120	125	105	139	134	138
BOD	3.9	3.6	3.8	3.8	3.6	3.8	3.7	3.6	3.5	3.7	3.9	3.8
DO	5.2	4.9	5.1	5.0	4.8	4.7	4.8	4.9	4.6	5.1	5.1	5.0

Table 6. Physicochemical analysis of water sample of station 3. Skebi Lake.

Parameters	Months											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Temp: Air	21	23	26	31	32	39	44	40	32	26	23	20
Tem: Water	19	20	23	27	29	36	40	36	29	23	20	17
pH	8.5	8.6	9.0	8.5	8.7	8.7	8.5	8.8	8.2	8.9	8.4	8.6
EC	1327	2190	1270	1250	1194	1230	1054	1180	983	1246	1127	1110
TDS	9827	8965	**10,420**	9547	8974	9657	7590	8540	6580	7890	8936	9570
Turb	0.27	0.23	0.29	0.24	0.25	0.27	0.23	0.25	**0.20**	0.26	0.29	0.28
Ca	728	745	772	710	685	715	680	672	582	720	782	730
Mg	838	782	**876**	816	782	725	678	698	645	763	812	804
Hard	5428	5160	**5536**	5096	4528	4826	3974	4976	3792	5120	5265	5380
Alkal	3.8	3.5	3.4	3.3	3.2	3.7	3.1	3.2	3.0	3.7	3.6	3.5
Cl	3329	3289	**3418**	3370	3236	3190	3075	2987	2868	3145	3185	3276
Na	52	50	46	54	58	45	48	47	42	48	49	50
K	**182**	159	170	180	162	150	156	169	140	160	172	157
SO_4	**2980**	2896	2937	2765	2830	2696	2589	2752	2438	2686	2845	2810
HCO	—	—	—	—	—	—	—	—	—	—	—	—
HCO_3	182	153	170	167	162	146	156	149	140	148	172	160
BOD	4.2	4.1	4.0	3.9	4.0	4.0	3.9	3.9	3.8	4.0	4.1	4.0
DO	5.5	5.3	5.4	5.2	5.3	5.4	5.1	5.2	5.0	5.3	5.2	5.1

Table 7. Physicochemical analysis of water sample of station 4. Tooti Lake.

Parameters	Months											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Temp: Air	21	25	26	33	37	41	42	39	32	26	23	20
Tem: Water	19	22	23	30	33	38	39	36	29	23	20	17
pH	9.2	9.0	9.1	8.7	8.8	9.0	8.5	8.6	8.3	8.4	8.9	8.8
EC	7984	7878	7920	7636	7180	7280	6568	6892	5872	6972	6217	7684
TDS	5123	4976	5068	4783	4837	4690	4287	4528	4027	4686	4839	5074
Turb	38	32	33	37	30	36	28	29	24	31	35	34
Ca	**1214**	1180	1174	1168	1034	1149	983	1084	845	987	1128	1068
Mg	394	376	374	310	345	355	285	367	262	296	312	342
Hard	3985	3884	3923	3810	3812	3792	3529	3626	3428	3590	3782	3888
Alkal	2.9	2.3	2.64	2.4	2.5	2.2	2.1	2.5	**2.0**	2.6	2.8	2.7

Parameters	Months											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Cl	147	140	132	130	127	129	120	125	108	134	142	128
Na	75	72	69	71	62	73	56	54	48	66	72	70
K	23	21	18	19	16	20	14	22	15	17	21	22
SO_4	1915	1880	1819	1792	1725	1682	1528	1632	1372	1575	1882	1794
HCO	—	—	—	—	—	—	—	—	—	—	—	—
HCO_3	0.9	0.6	0.8	0.6	0.7	0.8	**0.5**	0.7	0.6	0.7	0.8	0.6
BOD	4.5	4.4	4.2	4.3	4.1	4.2	4.0	4.1	3.9	4.3	4.2	4.0
DO	5.4	5.1	5.3	5.1	5.2	5.3	5.1	5.2	5.0	5.3	5.2	5.1

Table 8. Physicochemical analysis of water sample of station 5. Dangewari Lake.

Parameters	Months											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Temp: Air	21	24	26	34	38	43	44	38	32	28	23	20
Tem: Water	19	21	23	30	35	40	41	34	29	24	20	17
pH	9.0	8.8	8.9	8.6	8.5	8.7	8.3	8.4	8.1	8.3	8.6	8.8
EC	8912	8842	8720	8254	7837	7632	6865	6540	5392	6934	6836	7894
TDS	5610	5495	5580	5324	4872	4670	4583	4264	3983	4685	4892	4975
Turb	**186**	183	180	172	162	148	152	138	106	162	170	180
Ca	492	471	482	465	385	390	328	387	295	348	412	426
Mg	782	735	757	708	628	615	573	628	412	593	684	710
Hard	4427	4350	4321	4230	4082	4150	3862	3764	3429	3927	4128	4250
Alkal	2.8	2.4	2.6	2.3	2.4	2.5	2.2	2.6	2.1	2.4	2.5	2.7
Cl	142	137	130	120	126	119	114	121	108	133	125	138
Na	54	49	46	44	42	43	37	39	32	46	41	40
K	8.0	8.4	4.0	7.5	5.0	6.8	6.0	8.7	7.0	6.5	9.0	8.9
SO_4	2286	2175	2213	2098	2145	1945	2096	2190	1827	1670	1273	1450
HCO	—	—	—	—	—	—	—	—	—	—	—	—
HCO_3	1.2	1.1	1.06	1.3	1.03	1.2	1.1	1.3	1.0	1.1	1.4	1.2
BOD	**4.6**	4.2	4.3	4.4	4.2	4.5	4.1	4.2	3.9	4.0	4.3	4.2
DO	5.1	4.8	5.0	4.9	5.0	5.0	4.9	4.8	4.7	4.8	5.0	4.9

Table 9. Physicochemical analysis of water sample of station 6. Kharari Lake.

Parameters	Months											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Temp: Air	20	24	26	30	37	41	44	38	32	27	23	20
Tem: Water	18	21	23	27	34	37	40	34	29	24	20	17
pH	8.0	7.8	7.9	7.6	7.7	7.9	7.5	7.8	7.6	7.8	7.7	7.9
EC	5489	5370	5282	5685	4827	5120	4628	4952	5273	5734	6190	5856
TDS	3186	3256	2973	3080	2863	2965	2682	2792	2854	3124	3340	3260
Turb	12.6	11.8	12.0	11.3	10.0	9.2	8.0	10.4	9.0	9.8	11.9	10.5
Ca	22	18	20	19	18	17	15	21	13	11	6	10
Mg	294	265	240	217	235	247	192	230	205	208	273	253
Hard	1082	978	926	912	884	890	836	992	928	985	1180	1005
Alkal	20.5	19.6	`19.8	18.7	19.2	20.2	16.2	17.6	18.5	19.9	21.4	20.7
Cl	603	568	583	590	535	528	483	610	528	630	666	642
Na	787	740	782	714	739	728	626	775	712	805	821	794
K	38	35	31	34	29	32	26	36	28	30	32	33
SO_4	937	883	826	694	793	782	638	728	875	635	1040	868
HCO	—	—	—	—	—	—	—	—	—	—	—	—
HCO_3	980	940	826	860	793	836	782	872	863	945	1070	984
BOD	3.7	3.6	3.1	3.5	2.9	3.4	**2.7**	3.3	2.9	3.2	3.0	4.4
DO	5.6	5.8	5.4	5.7	5.3	5.5	5.2	5.8	5.7	5.9	**6.1**	6.0

Table 10. Physicochemical analysis of water sample of station 7. Raja Pathan Lake.

Parameters	Months											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Temp: Air	21	25	26	34	39	42	**45**	40	32	26	23	20
Tem: Water	19	22	23	30	36	39	41	36	29	23	20	17
pH	8.8	8.7	8.4	8.6	8.2	8.4	8.5	8.3	9.0	9.1	**9.3**	8.9
EC	8379	8239	7838	5673	4570	6890	5820	7346	7739	8215	**9120**	8764
TDS	1529	1432	1482	1380	1273	1446	1382	1457	1528	1590	1690	1568
Turb	0.27	0.25	0.26	0.28	0.22	0.23	0.21	0.24	0.25	0.27	0.29	0.22
Ca	49	45	38	46	30	42	36	47	40	51	54	50
Mg	329	348	230	297	186	245	210	305	236	264	397	322
Hard	1626	1486	1327	1336	1182	1479	1268	1504	1529	1545	1770	1654
Alkal	67.4	59	48	51	43	49	50	62	60.2	57	**71.6**	68
Cl	320	316	257	286	216	265	237	248	285	317	397	304
Na	1125	1030	937	879	792	915	845	1056	1026	1187	**1231**	1115

Parameters	Months											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
K	67	70	53	56	47	58	52	60	62	57	72	55
SO_4	386	357	274	290	218	287	274	370	326	365	403	378
HCO	—	—	—	—	—	—	—	—	—	—	—	—
HCO_3	3428	3294	3028	3125	2793	2880	2983	3145	3218	3472	**3580**	3356
BOD	3.9	3.6	3.2	3.3	3.4	3.7	3.5	3.8	3.6	3.5	3.8	3.7
DO	5.6	5.5	4.8	5.3	5.0	5.1	5.2	5.0	5.4	5.7	5.8	5.2

Table 11. Physicochemical analysis of water sample of station 8. Old Nara Lake.

Parameters	Months											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Temp: Air	21	23	26	34	38	41	42	37	32	28	23	20
Tem: Water	19	20	23	30	35	38	39	34	29	25	20	17
pH	7.9	7.7	7.8	7.6	7.3	7.5	7.1	7.4	7.0	7.3	**6.9**	7.2
EC	1263	1143	1172	1092	938	1286	1027	1167	1263	1342	1495	1275
TDS	729	720	628	612	510	664	543	675	692	754	808	785
Turb	31	32	28	29	25	26	27	28	30	27	33	30
Ca	58	55	50	52	40	48	46	50	53	57	64	60
Mg	49	47	46	43	36	44	42	45	47	53	56	51
Hard	328	345	275	263	204	289	232	254	245	316	390	327
Alkal	4.3	4.4	4.0	4.1	3.9	4.7	4.1	4.4	4.2	4.5	4.8	4.6
Cl	152	148	138	119	110	134	126	160	135	145	166	141
Na	141	128	136	130	106	128	124	133	130	140	150	137
K	17	14	16	15	12	13	4	11	5	9	18	17
SO_4	239	215	143	178	137	198	153	232	172	214	260	243
HCO	—	—	—	—	—	—	—	—	—	—	—	—
HCO_3	210	225	189	194	145	178	162	196	186	224	240	210
BOD	3.8	3.7	3.5	3.6	3.3	3.5	3.0	3.4	3.1	3.2	3.6	3.3
DO	5.0	4.8	4.9	4.9	4.8	4.7	4.8	4.8	4.9	4.8	5.0	4.8

Table 12. Physicochemical analysis of water sample of station 9. Saedo Pattan Lake.

highest and lowest values (71.6 and 2.0 mg/L) for alkalinity were measured in November and September, respectively (**Tables 8**, **11**). The highest and lowest values (3418 and 22 mg/L) for Cl were measured in March and May, respectively (**Tables 7**, **13**). The highest and lowest values (1231 and 21 mg/L) for Na were measured in November and May, respectively (**Tables 10**, **13**).

Parameters	Months											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Temp: Air	21	24	26	33	35	40	43	38	32	27	23	20
Tem: Water	19	21	3	30	31	36	40	34	29	24	20	17
pH	7.6	7.4	7.2	7.3	7.0	7.2	6.9	7.1	7.0	7.5	7.3	7.1
EC	528	512	489	537	**364**	464	387	486	472	515	596	564
TDS	312	302	307	289	**214**	289	230	267	278	307	321	298
Turb	162	157	147	137	117	118	26	127	145	167	180	172
Ca	47	49	53	51	38	45	42	51	48	50	60	54
Mg	18	15	17	13	4	**12**	15	14	16	15	19	17
Hard	210	208	203	198	**140**	212	154	168	182	185	230	217
Alkal	3.5	3.3	3.4	3.2	3.1	3.3	3.0	3.5	3.1	3.2	3.6	3.4
Cl	30	31	29	27	**22**	28	25	26	28	30	32	29
Na	31	28	30	25	**21**	24	27	26	29	28	33	30
K	7.0	6.8	6.0	6.2	5.0	5.4	**3.0**	4.8	5.0	5.9	4.0	4.7
SO_4	61	55	47	44	**38**	43	40	49	46	56	69	62
HCO	—	—	—	—	—	—	—	—	—	—	—	—
HCO_3	171	156	154	128	104	145	120	138	125	167	180	171
BOD	3.9	3.7	3.5	3.8	3.3	3.4	3.1	3.6	3.2	3.5	3.8	3.4
DO	5.0	4.8	4.9	4.8	4.7	4.8	4.6	4.9	4.8	4.7	5.0	4.9

Table 13. Analysis of physicochemical parameters of water sample for station 10. Nara Canal Chundiko.

The highest and lowest values (182 and 3 m/L) for K were measured in January and July, respectively (Tables 7, 13). The highest and lowest values (2980 and 38 mg/L) for SO_4 were measured in November and May, respectively (**Tables 7**, **13**). The highest and lowest values (3580 and 0.5 mg/L) for HCO_3 were measured in November and July (**Tables 8**, **11**) while the value of 0 for HCO was measured in all the months of the study period (**Tables 4–13**). The highest and lowest values (4.6 and 2.7 mg/L) for BOD were measured in January and July, respectively (**Tables 9**, **10**). The highest and lowest values (6.1 and 3.7 mg/L) for DO were measured in November and July, respectively (**Tables 4**, **10**).

4. Discussion and conclusion

The Nara Desert Wetland Complex (NDWC) encompasses sandy dunes, steep hills and includes low lying flat zones associated with different natural wetlands formed from the seepage of Nara Canal. These different wetlands are the major perennial source of water for the agricultural lands, local communities, wildlife and grazing livestock. NDWC comprises more than 225 seasonal and permanent, small, medium and large-sized lakes/wetlands. The total area of Nara

Canal is distributed from Sorah (Sukkur) to Head Jamrao about 108,960 hectares and Nara Canal was declared in 1972 as a Game Reserve area for the protection of wild animals. The NDWC is also recognized as an essential potential Ramsar Site [1–5]. The different floral habitation distributed in the Nara Desert includes phytoplankton, reed vegetation, herbs, shrubs and trees. The area is ecologically-rich with the faunal biodiversity which includes zooplankton, invertebrates, fishes, amphibians, reptiles, birds, small and large mammals. The NDWC has received high economic, social, floral and faunal habitats, and aquatic biodiversity values because the local communities are directly or indirectly dependent on these natural sustainable resources [1–4, 7, 29, 35] (**Figure 7**).

In the area the water quality and recharged by the Nara Canal is mainly sweet and acceptable ranges of TDS between 500 and 800 ppm except hypersaline lakes. The hypersaline water of desert area is mainly observed brackish which have TDS between 10,000 and 28,000 pp. [5, 36].

The climate of the area is mainly arid having high temperatures and late summer rains observed. The seasonal rainfall is varied and is less than 250–300 mm and rainy season usually starts from June to September. Before the monsoon season, the average temperature is exceeding 45°C in the desert region and in the plains of NDWS the average temperature between 30 and 40°C. The wetland complex is recognized of great hydrological values as 98% Nara Canal water is used for agriculture and only 2% water is used for domestic and drinking purposes. The wetland complex of Nara Canal is 361.6 km long and 90–135 m wide. The maximum water depth of wetland complex is 7.5 m. The highest water discharges of Nara Canal are reported in the months of May–July and the minimum water flow in the August [1–4, 7].

The assessment of physicochemical parameters such as pH and alkalinity revealed that the lake water has mostly remained alkaline during the whole study period except the Nara Canal station due to its input of rain water. The range of hardness was higher in most of the selected lakes of NDWC. The acceptable level of hardness in lake waters is recognized as 200 mg/L by the World Health Organization [34]. The physicochemical parameters of Na and Mg, as well as

Figure 7. A view of Nara Canal Khairpur.

the EC, TDS concentrations were found to be higher than the WHO standard. The Na is the major solute that can also affect aquatic biodiversity [37]; Na concentrations during the study period were higher than WHO accepted standard in most of the wetlands in the NDWC. The WHO recommended that the tolerable level of Cl is 250 mg/L [34]. In this study, the various wetlands had higher Cl concentration than the acceptable WHO standard. However, the concentrations of Ca, K, SO_4, HCO_3, BOD and DO were higher than the acceptable WHO standard in the most of selected wetlands during the study period.

In the study area, quality of water is mainly sweet and acceptable for drinking purposes. The range of Total Dissolved Solids (TDS) reported between 500 and 800 ppm. In the area, there are also few brackish wetlands reported and TDS varies between 10,000 and 28,000 due to recharge of insufficient amount of water. The quality of ground water is mainly dominated by sulfate, chloride, calcium and magnesium ions [16, 38, 39]. The conductivity (or TDS) is major parameter along with pH in recognizing the water quality. The values of both parameters is considered acceptable in freshwater lakes while it is otherwise considered the saline lakes. If the value of turbidity is higher than considering alkaline water while above the WHO standard level of 5 NTU. The value of higher turbidity may be due to discharge of waste materials and agriculture run off. The Nara Canal is originates from the Indus River. The water in the Indus River is generally contaminated carrying organic and inorganic polluted particles load from the upstream due to anthropogenic activities. The Sindh Environmental Protection Agency (SEPA 2002) recorded that the value of BOD in Indus River is exceeds more than 6.5 mg/L, which is also recognized by Global Environmental Monitoring System (GEMS) the water of Indus River is highly polluted. According to microbiological analysis of water by WWF-Pakistan (2007) confirmed that in the two sites the presence of fecal coliform. The availability of Fecal coliform in the water system is considering harmful for the human population consumption which may cause water borne disease. In freshwater bodies the availability of Fecal coliform is an indicator of contamination with the human and animal excreta [5, 7, 36, 38, 40, 41].

The parameters of water were only collected to examine the quality of water for the purpose of drinking. Although, it has also been reported that the more than 100,000 fisherman population who were directly associated with the fishery occupation have suffered a lot in the recent decades. In the wetland complexes the higher amount of inflow of saline effluent has causing in the devastation of the lake [7, 40].

5. Threats

Hunting: In the study area, the hunting for recreation is observed common and uncontrolled. However, the region is protected but there is no effective implementation of the wildlife laws for the wild animals. Due to hunting pressure, this is also leading to imbalance between the predator and prey species.

Foraging of Livestock: The large amount of grazing livestock in the area together with the recent climatic changes is degrading the food chain in the ecosystem dynamics.

Cutting trees: In the study area, the cutting of trees in the adjoining desert region for continuous practice of conversion of lands into agricultural fields which is affecting the wild population.

Developmental activities: In this modern era the human population is increasing in higher rate and habitation, the developmental activities in the region and conversion of land for the purpose of agriculture has been damaging the wild habitat and ultimately increasing stress on the existing wildlife.

Recommendation:

Controlled hunting: To control the hunting the check posts should be established for keeping vigilance at important points on uncontrolled hunting. Due to shortage of infrastructure in Sindh Wildlife Department like as transport system and staff failed to stop hunting so that the officials must enhance staff and transport. The Wildlife authorities must consider strengthening of Sindh Wildlife Department in the region.

Ecotourism: The area of Nara Wetland Complex is a best site for promoting ecotourism. For sighting of wildlife and bird watching the watch towers at potential points and other facilities should be developed for promoting community based conservation tourism. The people of local community should be participated and benefited from all this tourism activates. From local community the youth should be trained as a volunteers and co-guides. These health activities will provide the incentives to the local community as a source of income generating activity and an alternative livelihood source.

Promote participatory wildlife management and conservation: For promoting participation in wildlife management and conservation the institutional capacity of community based organizations in the region should be developed.

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Conflict of interest

The research study of "Ecology and Environmental Assessment of Nara Desert Wetland Complex, (NDWC) Khairpur, Sindh-Pakistan"; has there is no conflict of interest.

Notes/Thanks/Other Declarations

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Acronyms and Abbreviations

Tem	temperature
pH	pH
EC	electrical conductivity
TDS	total dissolved solids
Tur	turbidity
Ca	calcium
Mg	magnesium
Hard	hardness
HCO	carbonate
HCO_3	bi-carbonate
Alkal	alkalinity
Cl	chlorides
Na	sodium
K	potassium
SO_4	sulfate
BOD	biological oxygen demand
DO	dissolved oxygen
NDWC	Nara Desert wetland complex
WHO	World Health Organization
WWF	Worldwide Fund for Nature

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Chapter 5

Sand Electrification Possibly Affects the Plant Physiology in Desertification Land

Li Xingcai

Additional information is available at the end of the chapter

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Abstract

At present, the researchers mainly focused on the degradation of vegetation caused by the sand burial, the sand flowing, and the loss of soil moisture and nutrients but never considered the impact of strong environmental electric field, which caused by the moving sand particles, on the physiological process of plants. In this chapter, we briefly introduced the research progress of wind-blown sand electrification and proposed a coupling prediction model to explain the contact electrification phenomenon of moving sand. At last, based on the rigid conduit model and the root-water-uptake model, we discussed the effect of wind-blown sand electric field, which maximum value can reach to 200 kV/m, on the speed of plant sap flow, the water potential of root, and the cell membrane permeability, respectively. The numerical simulation results showed that the wind-blown sand electric field directly accelerates the sap flow rate and indirectly decreased the water potential of plant root, which finally affects the plant physiological processes. These results can explain why the effect of wind-blown sand on the plant is obvious than that of the clean wind. From these discussions, we effectively illustrate the impact mechanism of wind-blown sand on the plant physiology in the desertification land.

Keywords: wind-blown sand electric field, water transport velocity, root-water uptake, cell membrane permeability

1. Introduction

Desertification is one of the major environmental disasters in the world [1, 2]. Desertification not only leads to the loss of agriculture and threat to the human survival but also can increase the aerosol concentration, degrade the atmospheric quality, and then lead to some negative impacts on the environment and human health [1, 3, 4]. In general, land desertification is accompanied by the degradation of vegetation [5] and accelerated by the climate anomalies and drought. Some researchers studied the reason of vegetation degradation and its restoration techniques under the various environmental stresses, for example, the drought [6], the high temperature [7, 8], the wind blowing [9], the sand burial [10, 11], the sand flowing [12, 13], the dust deposition on plant leaf [14], and so on.

In addition, some scholars also discussed the influence of various electric fields on the biological system [15]. Murr firstly discussed the physiological influence on plant growth of the electric field environment, and the author found that sufficiently high electric fields have a definite effect on plant growth and the growth response. Andersen and Vad [16] investigated the growth of *Serratia marcescens* and *Escherichia coli* at various filed strengths. Some researchers also considered the effect of environmental electric field on the seed germination, plant growth, respiration, and tolerance [17–22].

On the other hand, the soil grain and the sand particles incompactly distribute on the surface of desertification land, which can be driven by the strong wind and eventually formed the wind-blown sand flowing. Some particles will deposition on the earth, but others can enter into the air with the turbulent process and even develop to the dusty weather [23, 24]. A lot of experiments show that the moving sand is charged, which induced a strong electric field in the air [25–27]. As mentioned above, some experimental results have shown that with the increasing of the applied electric field, the electrostatic field has some negative or positive influence on the plant physiological processes. The wind-blown sand electric field must also work on the similar process.

However, there is no any related report published on the effect of wind-blown sand electric field on the plant physiological processes. In view of this situation, this chapter firstly introduced the research status of sand electrification phenomenon and then proposed some physical models to analyze the effect of environmental electric field on the physiological processes of plants, for example, the root-water absorption process, the water transport processes in the stem, the permeability of cell membranes, etc. Through these discussions, we want to furtherly demonstrate the influence of sand flow on plant growth.

2. Contact electrification of moving sand

Knowledge on the phenomenon of sand electrification also stems from a few experimental measurements. For example, friction was performed between the glass rod and the filter paper, whose main components were similar to the sand particles, and then the charge on the glass rod was measured by an electroscope and a Faraday cup [28], or blasting sand were measured [29, 30]. These experiments showed that the larger particles tend to be charged positively, but the smaller particles are charged negatively [31]. In addition, they also find that the atmospheric pressure [32], the ambient humidity [33, 34], and the components [35, 36] all have some significant impact on the particle's charged process [36].

With the development of experimental devices, some scholars found that the polarity of the charge on a particle is related to its grain size. Greeley and Leach [37] analyzed the wind tunnel experimental results, and he finds that the critical particle size is 60 μm. But Zheng et al. found that the negative charge is gained when the diameter is smaller than 250 μm and positive charge is gained if the diameter is larger than 500 μm [38, 39], which have been proven by Forward et al. [40]. Of course, the critical particle size for the charged polarity of sand maybe varies with the incoming wind velocity, the height from the sand surface, and the grain size, as well as its size distribution [25].

It should be specially pointed out that the above researches only obtained the average charge on particles. Due to the limitations of experimental techniques, the experimental devices, and other objective factors, we cannot precisely obtain the quantitative relationship between the charge on single particle and the particle size, the incoming wind speed, the temperature, the humidity, and so on. However, these results have played a positive role in promoting the understanding of the electrification phenomenon of wind-blown sand and enlighten scholars on its physical mechanism.

On the mechanism of contact electrification of sand, the highly accredited conjecture is the contact electrification and the polarization-inducing process [25, 41]. For the contact electrification mechanism, which contains the static contact and the friction, an asymmetric transfer of tiny charged ion or substance is the primary source of it. In addition, it just concerns what these metastatic substances are and why and how many are transferred. But the polarization-inducing process is more intuitive. This mechanism suggests that the particle is polarized by the environmental electric field and the excess charges are repelled to the two sides of the particle. When the moving particle contact with each other, charges with opposite polarity cancel out and then will charge itself after separation. This theory firstly explained the reason of the thunderstorm. Considering that the natural sand is wrapped by a water film [42, 43], some researchers also believed that it also worked in the electrification of wind-blown sand [41]. However, there is still a lack of physical model which is formed by the fusion of those two physical processes. In here, I want to introduce a simple coupling model for it.

2.1. Contact electrification from ion transfer

Xie et al. [44] proposed a contact electrification model of glass sphere, which can precisely predict the effect of particle size and the impact velocity on the electric quantity. So here, we directly used it to express the contribution of ion transfer to the contact electrification process. Of course, you can replace it with other suitable models, which have more precision. The model can be expressed as follows:

$$Q_1 = \rho P_D(1 - P_D)(\mathrm{A}_2 - \mathrm{A}_1) \tag{1}$$

where ρ is the charge density and P_D is the probability of any position on the particle surface as a donor; the reference suggests that it is 0.5. $A_i(\mathrm{i} = 1, 2)$ is the contact area in the collision process, which can be expressed as follows:

$$A_1 = 2\pi R_1^2\left(1 - \sqrt{R_1^2 - 2R\delta_{\max}^1}/R_1\right) A_2 = 2\pi r_1^2\left(1 - \sqrt{r_1^2 - 2R\delta_{\max}^2}/r_1\right)$$

$$\delta_{\max}^1 = \frac{R_1}{R_1 + r_1}\left(\frac{5}{4}\frac{M}{K}v_r^2\right)^{0.4} \delta_{\max}^2 = \frac{r_1}{R_1 + r_1}\left(\frac{5}{4}\frac{M}{K}v_r^2\right)^{0.4}$$

$$R = \frac{r_1 R_1}{r_1 + R_1} \; M = \frac{m_1 m_2}{m_1 + m_2} \; E = \left(\frac{1 - \nu_1^2}{E_1} + \frac{1 - \nu_2^2}{E_2} \right)^{-1} \; K = {}^{4ER^{0.5}}/_{3}$$

In here m_1, m_2 is the mass of two particles with radius R_1, r_1, E_i, ν_i is its elastic modulus and Poisson's ratio, and v_r is the collide velocity.

2.2. Polarization-inducing process

The atmospheric electric field is 100–200 v/m, but it may be up to hundreds of kilovolts per meter in the thunderstorm or dust storm [45]. Under the polarization of the electric field, the conductor particles also can be charged after being separated from contact. Latham and Mason [46] deduced the contact electrification of two conductive spheres under the electrostatic field:

$$\Delta q_0 = \gamma_1 E r^2 \cos\theta + \gamma_2 q_1 R_1^2 / r_1^2 \tag{2}$$

Here, E is the environmental electric field. r is the particle radius and θ is the angle between the two particles' centers and the electric field line. $q_i (i = 1, 2)$ is the initial net charge on the particle before they collide. The first term in Eq. (2) represents the contribution from the polarization, and the last one is the charge redistribution on the charged sphere. Here, we just keep the first term. Those meanings of the charge after two spheres collide in the electric field can be calculated through the last equation:

$$\Delta q_1 = \gamma_1 E r^2 \cos\theta \tag{3}$$

If two particles all are charged before they contact, the charge may redistribute on each surface. Davis [47] and Ziv and Levin [48] proposed a simple relation:

$$\Delta q_2 = (\omega - 1) q_1 + \omega q_2 \tag{4}$$

here, ω is the transfer fraction, which means how many charges on the smaller particle transfer to the relative larger particle. γ_1 is a parameter related to the radius ratio of two particles. And, we set $\alpha = r/R$, and then the values of γ_1 and ω have been shown in **Table 1**.

To simply, we obtain a fitting relationship used the MATLAB software, and it is shown as follows:

$$\gamma_1 = 1.915\alpha^2 - 6.132\alpha + 4.894$$

$$\omega = 0.5152\alpha^3 - 0.8769\alpha^2 - 0.1397\alpha + 1.003$$

α	0	0.2	0.4	0.6	0.8	1
γ_1	4.93	3.9	3.1	2.55	2.06	1.64
ω	1	0.948	0.838	0.714	0.6	0.5

Table 1. Values for the parameters γ_1 and ω.

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So, the charge on the smaller particles after it contacts another sand in a strong electric field can be obtained:

$$\Delta Q_1 = \Delta q_1 + \Delta q_2 \tag{5}$$

Considering that the sand is not an imperfect conductor, and the contact time is finite, so we have to add the impact of relaxation time [48]. Then, Eq. (6) is replaced by the following equation:

$$Q_2 = \left[1 - \exp(-\mathrm{t}_c/\tau)\right]\left(\Delta q_1 + \Delta q_2\right) \tag{6}$$

$\beta = 1 - \exp(-\mathrm{t}_c/\tau)$, t_c is the contact time, while particles collide each other. τ is the surface conductivity of sand, which is connected with the thickness of water film, denoted as n, on the sand:

$$\tau(\mathrm{n}) = \begin{cases} 3.0 \times 10^{-18} \times 10^{0.44n} & n > 0 \\ 6.5 \times 10^{-18} & n = 0 \end{cases}$$

If the air humidity is H, the thickness of water film can be calculated by the following equation:

$$n = -1.588 \times 10^{-6} x^4 + 2.567 \times 10^{-4} x^3 - 0.01193 x^2 + 0.2999 x + 0.02099$$

Based on the above equations, the electrification of sand contact in a strong electrostatic field can be forecasted.

2.3. Electrification of sand in sand flowing

Under the real conditions, both of the above two processes occurred when the particles contact each other. So, the total charge on sand can be calculated through Eq. (7):

$$Q = Q_1 + Q_2 \tag{7}$$

2.4. Discussions

We supposed the particles are colliding along its center line; the radius of larger sand is 6 mm, the radius ratio is 0.5, the humidity of sand is 0.1, the collision velocity is 0.5 m/s, and E_i, ν_i are all 15 GPa and 0.4. Taking into account these parameters, we discussed the effect of environmental electric field on the contact electrification of sand. The simulation results are shown in **Figure 1**. From it, we can see that while the environmental electric field is up to 100 kv/m, the charge increased by 10%. Considering that the wind-blown sand electric field may be up to 200 kV/m, we believe that the polarization-induced electrification mechanism plays a very important role in the phenomena of wind-blown sand electrification.

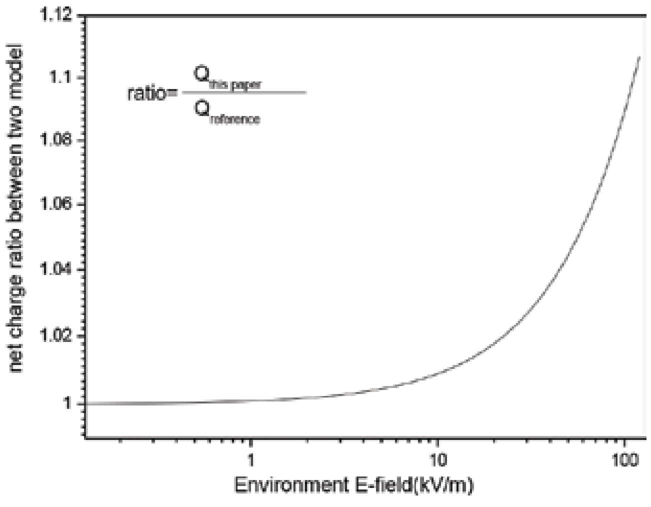

Figure 1. The effect of environmental electric field on the sand's electrification.

3. Wind-blown sand electric field

On the research of wind-blown sand electric field, Rudge firstly found that the atmospheric electric potential is obviously enhanced in the dusty weather and the direction is reversed [49]. Gill found the strong electric field and the spark phenomenon in the dust storm [50]. Freier found that the electric field in strong dust storm can be up to 60 kV/m [51]. Schmidt et al. measured the electric field in sand flow, and they found the electric field up to 160 kV/m at a distance of 5 cm from the ground [52]. These researchers just measured the vertical electric field. Jackson and Farrell found that the horizontal electric field of dust devil can be up to 120 kv/m [53]. Bo and Zheng found that the horizontal electric field is much larger than the vertical electric field [27]. Zhang et al. measured the electric field range from 0 to 30 m, in the sand

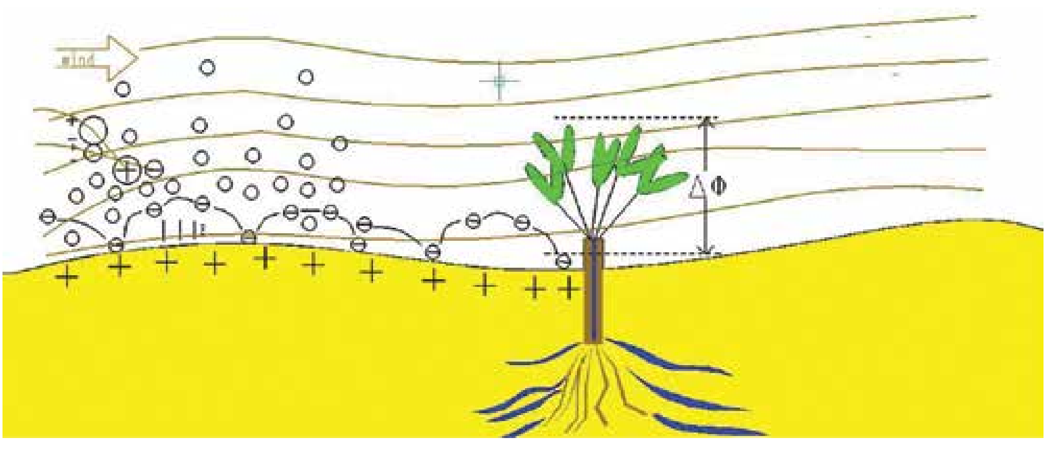

Figure 2. The effect of wind-blown sand electric field on plant.

storm, and they found that the electric field is no-monotonic changed with the increase of height in the process of sandstorm and the direction may reverse [54]. These studies further revealed the complexity of wind-blown sand electric field, but they all reported that the magnitude of electric field is generally tens of kilovolts per meter, and it is even up to more than a hundred kilovolts per meter, which is sufficient to affect the physiological processes of plant (**Figure 2**).

4. Effects of sand electrification on plants

Numerous studies have shown that the electric fields, as a physical stimulus, have a wide range of effects on the physiological processes of plant; for example, an appropriate strength of the electric field can affect cell proliferation, enzyme activity, biofilm permeability, and DNA synthesis, which will have an impact on plant growth and even improve the plant tolerance [21]. Some experiment also reported that the high-level electric field accelerated the drying of the hydrous plants [21]. In general, plants used to adapt a couple of abiotic effects like drought, ice, and sandstorm causing spectacular physical damage in plant tissues, especially the psammophyte. However, the psammophyte is the product of evolution, but others are more common, which would not adapt the damage from electric field, for example, the crop on the desertification land. In my knowledge, no any references concerned about the impact of wind-blown sand electric field on plant's physiological processes. In this chapter I want to discuss the effect of environmental electric field on the plant sap flow, the potential root water, and the cell membrane permeability.

4.1. Effect on plant sap flow and root absorption

For the part between the crown and the root, which also named as xylem duct system, Parlange et al. proposed a theoretical model to simulate the sap flow of plant, and he suggest that the Poiseuille equation can be used to describe the sap flow in the stalk [55]. The driving force of the sap flow is the water potential differences between the plant root and the soil water. We set it as Δp. The water flux in a duct of the stem can be calculated through the Poiseuille equation:

$$Q = \frac{\pi r^4}{8\eta L}(\rho g \Delta h + \Delta p) \tag{8}$$

here, Q is the water flux, r is the duct radius, L is the duct length, Δh is the height difference of the duct, η is the fluid viscosity coefficient, and $\rho g \Delta h$ represents the gravity of water in the duct.

It is clear that Eq. (8) does not consider the effect of environmental electric field. The plants in desertification land are located in a strong wind-blown sand electric field. The duct of the stem can be equivalent to tubules, the water in the duct can be simplified to a tiny conductor rod,

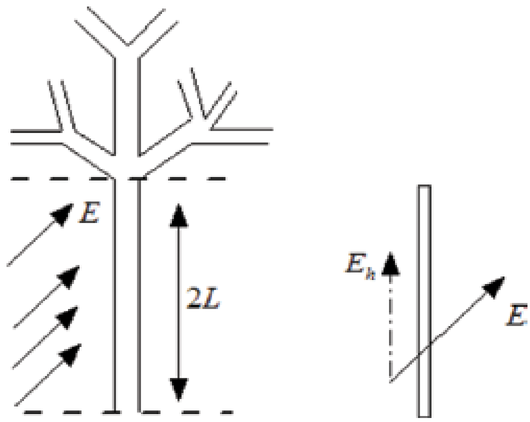

Figure 3. The plant in wind-sand electricity field.

and it must be affected by the electrostatic field force. So, we need to add one term in Eq. (8) to describe the effect from electric field (**Figure 3**).

If we set the vertical height of stem as $2L$, the electric field is E_h, σ_h is the polarization charge density, and the electric field force can be calculated through Eq. (9):

$$F_E = \int_{-L}^{L} \sigma_h E_h dh \tag{9}$$

$\Delta h = 2L$. To simplify, we set that the environment electric field is equivalent to the field in the stem duct, and we directly use the experimental results of wind-blown sand electric field reported by Schmidt et al. [52]:

$$E_h = E_0 h^{-0.6} \tag{10}$$

here, E_0 is a constant and h is the height from the ground. The charge on the water rod is [56]:

$$\sigma_h = \frac{E_h h}{\ln\left(4\left(L^2 - h^2\right)/a^2\right) - 2} \tag{11}$$

Now, we can obtain the electric field force on the water rod:

$$F_E = \int_{-L}^{L} \frac{E_0{}^2 h^{-0.2}}{\ln\left(4\left(L^2 - h^2\right)/a^2\right) - 2} dh \tag{12}$$

Then, we can modify Eq. (8) to contain the effect of electric field:

$$Q = \frac{\pi r^4}{8\eta L}\left[\rho g \Delta h + \Delta p + \mathrm{sign}(E) * F_E\right] \tag{13}$$

The corresponding flow velocity is

$$v = Q/\left(\pi r^2\right) = r^2(8\eta L)^{-1}[\rho g\Delta h + \Delta p + \mathrm{sign}(E) * F_E] \tag{14}$$

Based on Bernoulli's theory, the change of fluid velocity can induce the change of pressure. Those meanings of the electric field also can influence the root absorption process. Therefore, we need to find a related model to describe it.

Supposedly, the resistance of radial direction and the one of axial direction for root absorption are $R_R\, R_X$, and they all keep constant. In addition, supposedly the water potential inside and outside the root is $\psi_s(z)$, $\psi_X(z)$, the water flux from soil to root is $q_R(z)$, the radial resistance for the root absorption is R_R, and the following relation is established:

$$R_R q_R(z) = \psi_s(z) - \psi_X(z) \tag{15}$$

here, z is the distance to the root tip; for the root tip, $z = 0$.

The water potential gradient along the root equals to the axial flux of root water in unit length: so,

$$\frac{d\psi_X(z)}{dz} = -R_X q_X(z) \tag{16}$$

$q_X(z)$(mm^{-3}-s^{-1}) is the volume flux of water from soil to root, which can be calculated through the van den Honert's constant flow equation:

$$\frac{dq_X(z)}{dz} = 2\pi a q_R(z) \tag{17}$$

here, a can be thought as the radius of stem duct.

After some mathematics calculation, we can obtain

$$\frac{d^2\psi_X(z)}{dz^2} = \frac{2\pi a R_X}{R_R}\left[\psi_X(z) - \psi_s(z)\right] \tag{18}$$

Eq. (18) can be used as the control equation of root suction model.

The water potential function ψ_s must vary with the research region. For example, the linear function can be used for the region where plant with shallow roots and well irrigation, and the exponential function can be used to describe the region with large changes in geological condition and climatic conditions and the plant with deep roots.

(A) Soil water potential is linear function.

We supposed the soil water potential is

$$\psi_s(z) = \mu z + \psi_0 \tag{19}$$

In here μ is an experimental constant, and we set it as 0.5. z is the distance from the soil surface. The water potential at root cap $\psi_X(L)$ is

$$\psi_X(z)\big|_{z=L} = \psi_X(L) \tag{20}$$

At the influence of environmental electric field, the sap flow is accelerated. Considering the Bernoulli equation, the parameter $\psi_X(L)$ can be predicted as follows:

$$\psi_X(L) = k/v^2 \tag{21}$$

In here v is the velocity of the stem flow at $z = L$, which can be calculated by Eq. (14). k is an experimental constant, and we set it as 0.5.

In addition, considering the cross section of root tip is too small, we set.

$$q_X(0) = 0 \tag{22}$$

Now, we can obtain that the water potential in root is

$$\psi_X(z) = \left[\psi_X(L) - \left(\mu z + \psi_0\right)\right]\frac{\cosh(\alpha z)}{\cosh(\alpha L)} + \frac{\mu}{\alpha}\frac{\sinh(\alpha L - \alpha z)}{\cosh(\alpha L)} + \left(\mu z + \psi_0\right) \tag{23}$$

(B) Soil water potential is exponential function.

We supposed the soil water potential is as follow:

$$\psi_s(\mathrm{z}) = \psi_s(0)\mathrm{e}^{-\mu z} \tag{24}$$

μ is a constant. Then, we can obtain the water potential function in root:

$$q_X(z) = \mathrm{A}\mathrm{e}^{\alpha z} + B\mathrm{e}^{-\alpha z} - \frac{2\pi a\mu}{\left(\mu^2 - \alpha^2\right)R_R}\Psi_s(0)e^{-\mu z}$$

$$\frac{dq_X(z)}{dz} = \mathrm{A}\alpha\mathrm{e}^{\alpha z} - B\alpha\mathrm{e}^{-\alpha z} + \frac{2\pi a\mu^2}{\left(\mu^2 - \alpha^2\right)R_R}\Psi_s(0)e^{-\mu z}$$

$$\psi_x(\mathrm{z}) = \psi_x(0)\mathrm{e}^{-\mu z} - \frac{R_R}{2\pi a}\left[\mathrm{A}\alpha\mathrm{e}^{\alpha z} - B\alpha\mathrm{e}^{-\alpha z} + \frac{2\pi a\mu^2}{\left(\mu^2 - \alpha^2\right)R_R}\Psi_s(0)e^{-\mu z}\right] \tag{25}$$

$$G = \frac{R_R}{2\pi a}\left(\alpha e^{-\alpha L} + e^{\alpha L}\right) \quad M = \frac{\mu\psi_s(0)}{\mu^2 - \alpha^2}\left(\mu e^{-\mu L} + e^{\alpha L}\right)$$

$$A = \frac{2\pi a\mu}{\left(\mu^2 - \alpha^2\right)R_R}\psi_S(0) - B \quad B = \frac{1}{G}\left[\psi_s(\mathrm{L}) - \psi_s(0)\mathrm{e}^{-\mu L} + M\right]$$

Now, we want to make some discussion on them.

Firstly, we showed the effect of electric field on the stem flow speed, which is shown in **Figure 4**. From it we can see that the velocity of stem flow obviously increased when we consider the effect of the environmental electric field, and it also increases with the stem radius increasing, but it decreases with the stem length increasing.

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Figure 5 showed the effect of electric field on the speed of stem flow, and we can see that the stem flow increases exponentially with the electric field increasing. From these two results, we can see that the effect of wind-blown sand on the plant is obvious than that of the clean wind.

4.2. Effect on the permeability of the cell membrane

For the dielectric response of the cell media under the electric field, the weak conductor-coated spherical model proposed by Prodan et al. can be used directly [57]. We used it to simplify expression derived by Di Biasio A. [57]:

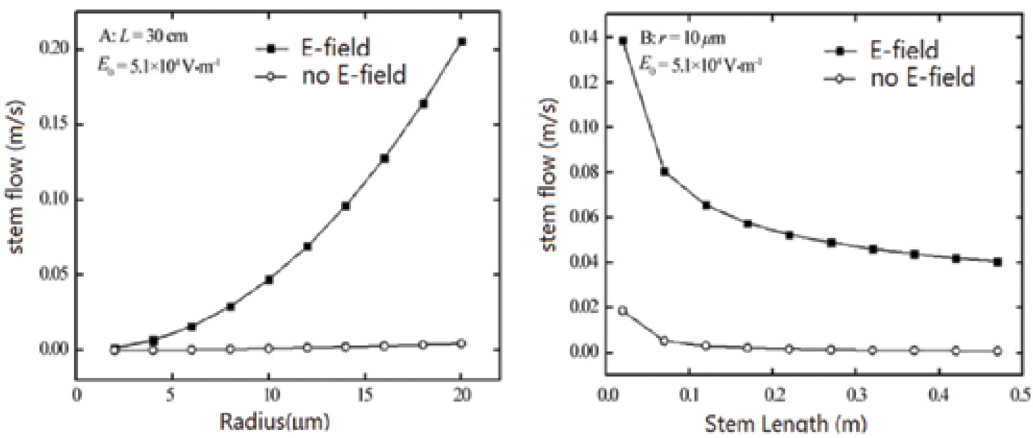

Figure 4. The effect of stem parameters on the stem flow.

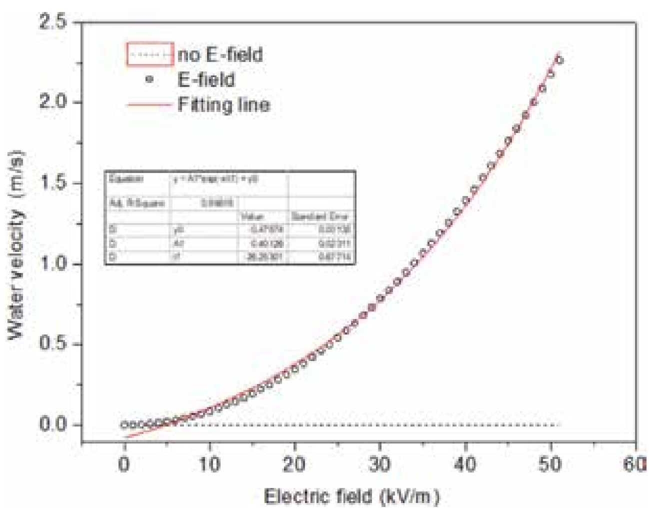

Figure 5. The effect of environmental electric field on the speed of stem flow.

$$\psi(r,\theta) = \left\{-rE_0 + 3R_1^2 E_0 \left[p_1 \nu(r,R_1) + p_2 \nu(r,R_2)\right]\right\}\cos\theta \tag{26}$$

In here $p_1 = \frac{C-B}{AC-B}$, $p_2 = \frac{A-1}{AC-B}$, and $D_k^{'} = 2D_k + i\omega R_k^2$, $k = 1, 2$. This expression is based on the spherical coordinates, r is radial component, and θ is azimuth angle (**Figure 6**):

$$A = \frac{1 + \frac{D_1^{'}}{2R_1\gamma_1}\left(\varepsilon_1^* + 2\varepsilon_0^*\right)}{1 + \frac{D_1^{'}}{2R_1\gamma_1}\left(\varepsilon_1^* - \varepsilon_0^*\right)} \quad B = \frac{R_2}{R_1}\frac{1\text{-}2\frac{D_1^{'}}{2R_1\gamma_1}\left(\varepsilon_1^* - \varepsilon_0^*\right)}{1 + \frac{D_1^{'}}{2R_1\gamma_1}\left(\varepsilon_1^* - \varepsilon_0^*\right)} \quad C = \frac{R_1^2}{R_2^2}\frac{1 + \frac{D_2^{'}}{2R_2\gamma_2}\left(\varepsilon_2^* + 2\varepsilon_1^*\right)}{1 + \frac{D_2^{'}}{2R_2\gamma_2}\left(\varepsilon_2^* - \varepsilon_1^*\right)}$$

$$\nu(r,R_1) = \frac{R_1}{3r^2} \quad \nu(r,R_2) = \frac{R_2}{3r^2} \quad (r > R_1)$$

$$\nu(r,R_1) = \frac{r}{3{R_1}^2} \quad \nu(r,R_2) = \frac{R_2}{3r^2} \quad (R_1 > r > R_2)$$

$$\nu(r,R_1) = \frac{r}{3{R_1}^2} \quad \nu(r,R_2) = \frac{r}{3{R_2}^2} \quad (r < R_2)$$

The electric potential difference between inside and outside of the cell is

$$\begin{aligned}\Phi &= \psi(R_1,\theta) - \psi(R_2,\theta)\\ &= 3R_1^2\left[p_1\left(\frac{R_2}{3R_1^2} - \frac{1}{3R_1}\right) - p_2\left(\frac{1}{3R_2} - \frac{R_2}{3R_1^2}\right)\right]E_0\cos\theta + E_0(R_1 - R_2)\cos\theta\end{aligned}$$

After further simplification, we obtain

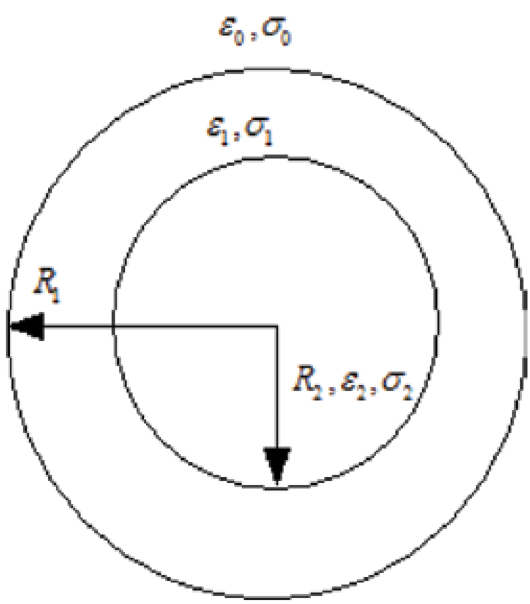

Figure 6. The coated spherical cell model and its physical parameters.

$$\Phi = 3\left[p_1\left(\frac{R_2}{3} - \frac{R_1}{3}\right) + p_2\left(\frac{R_2}{3} - \frac{R_1^2}{3R_2}\right)\right]E_0\cos\theta + E_0(R_1 - R_2)\cos\theta \tag{27}$$

The charged ion can be partially transported across the cell membrane and exchanged inside and outside the cell. For the $j - th$ ion, the net flux is

$$J_j = \frac{u_j RT}{\gamma_j}\frac{\partial \gamma_j c_j}{\partial x} - u_j c_j z_j F\frac{\partial E}{\partial x} \tag{28}$$

here, u_j is the ion mobility, R is the thermodynamic constant, T is the temperature, γ_j is the active coefficient in a solution, c_j is the ion concentration, z_j is the number of valence electron, F is the Faraday constant, and $\frac{\partial E}{\partial x}$ is the potential gradient.

In general, the first term repressed the ion flux originate from the concentration gradient, and the second term is stem from the potential gradient.

If we supposed that the active coefficient inside and outside the cell keeps a constant, then Eq. (28) can be changed:

$$J_j = u_j RT\frac{\partial c_j}{\partial x} - u_j c_j z_j F\frac{\partial \phi}{\partial x} \tag{29}$$

The thickness of cell membrane is Δx:

$$\frac{\partial E}{\partial x} = \frac{\Delta\phi}{\Delta x} = \frac{\Phi}{\Delta x}$$

Then, the last equation can be changed as follows:

$$\frac{z_j F\Phi}{RT\Delta x}dx = -\frac{dc_j}{c_j + \frac{J_j\Delta x}{u_j z_j F\Phi}}$$

Do some mathematic operation:

$$\int_0^{\Delta x}\frac{z_j F\Phi}{RT\Delta x}dx = -\int_{c_j^0}^{c_j^i}\frac{dc_j}{c_j + \frac{J_j\Delta x}{u_j z_j F\Phi}}$$

Then

$$\frac{z_j F\Phi}{RT} = \ln\frac{c_j^0 + \frac{J_j\Delta x}{u_j z_j F\Phi}}{c_j^i + \frac{J_j\Delta x}{u_j z_j F\Phi}}$$

And then

$$c_j^0 + \frac{J_j\Delta x}{u_j z_j F\Phi} = \exp\left(\frac{z_j F\Phi}{RT}\right)\left[c_j^i + \frac{J_j\Delta x}{u_j z_j F\Phi}\right]$$

So, we obtain the ion flux:

$$J_j = \frac{u_j z_j F\Phi}{\Delta x} \frac{1}{\left[\exp\left(\frac{z_j F\Phi}{RT}\right) - 1\right]} \left[c_j^0 + c_j^i \exp\left(\frac{z_j F\Phi}{RT}\right)\right] \tag{30}$$

Now, we will discuss the effect of environmental electric field on the ion flux in and out of the cell. The cell radius $R_1 = 1\mu m$, the thickness of cell membrane $d = 7nm$, its dielectric constant, and conductivity are $\varepsilon_1 = 150$, $\varepsilon_2 = 50$, $\varepsilon_0 = 80$, $\sigma_1 = 0.15$, $\sigma_2 = 0.2$, and $\sigma_0 = 0.1$; then the complex permittivity $\varepsilon_i^* = \varepsilon_i + \sigma_i/(i\varepsilon_m\omega)$, $i = 1, 2$, and $\varepsilon_m = 8.857 \times 10^{-12}$; the frequency of incident electric field $\omega = 10^3 Hz$, and the temperature $T = 300$K. In **Figure 7** we just showed the results, while $\theta = 0$. From it we can see that with the increasing of electric field, the negative ion flux increased, but the positive ion flux decreases, and the number of valence electron is larger; the influence is more obvious.

Figure 8 showed that the ion flux changed with the azimuth angle; from it we can see that with the increasing of azimuth angle, the net flux of positively charged ion became increased, but the one for negative valence ions decreases. In addition, with the increase of the number of valence electrons, the net flux of negative ions in the upper part of the cell is increasing, but the net flux of positive ions is constantly disappearing, which is opposite for the lower part of the cell. This is due to the opposite polarization charge in the upper and lower parts of the cell.

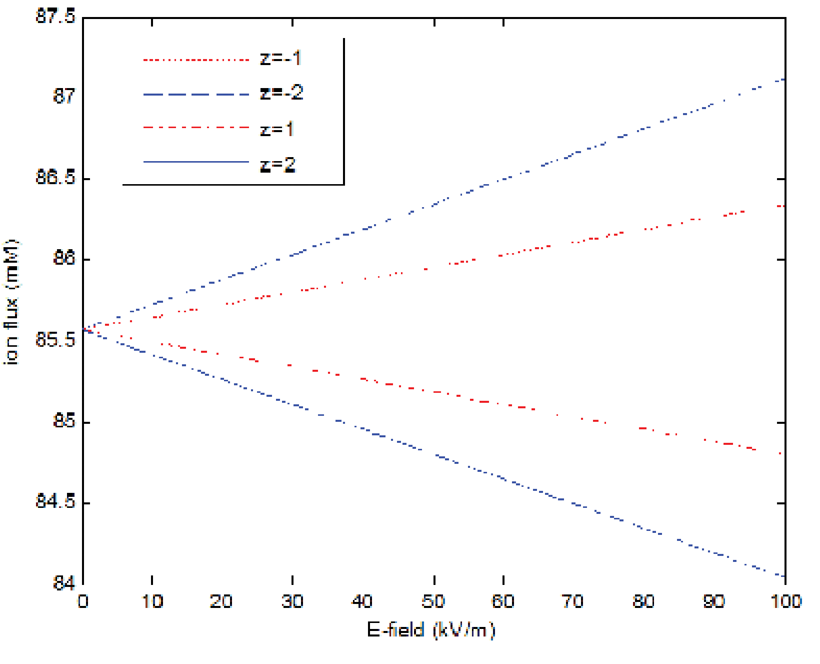

Figure 7. Effect of electric field on ion flux while it is with different polarity charges.

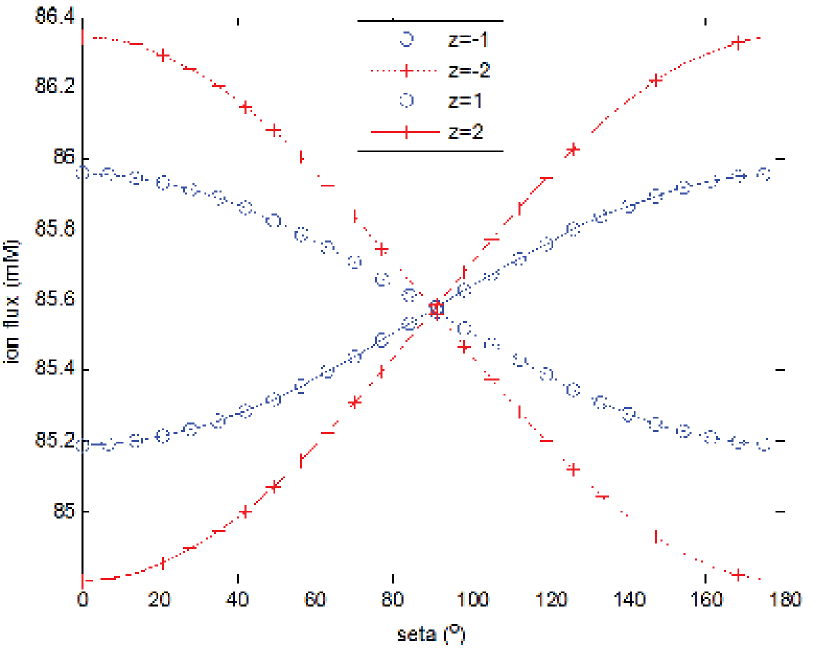

Figure 8. Ion flux changed with the azimuth angle (θ) of cell in spherical coordinate.

5. Conclusions and perspective

This chapter discussed the electrification of sand flow and proposed a simple physical model to reveal the mechanism of it. In addition, we also further discussed the effect of wind-blown sand electric field on the physiological process of plants. The simulation results showed that the electric field strongly enhanced the sap flow and root-water-uptake rate, and the permeability of the cell membrane also changed and then influences the growth of plants. However, these results are derived from the theoretical model, so we hope someone can carry out a series of relevant experimental studies to verify them. In addition, there is a lack of detailed experiment and discussion on the frequency of wind-blown sand electric field and on the effect of frequency of electric field on the plant physiology process.

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The aim and purpose of our book, Community and Global Ecology of Deserts, is to give an overview and report from the frontiers of desert ecological research.

The ecology of deserts as a scientific discipline plays a key role in solving many of global problems due to collective adaptation methods and approaches of lifeforms living in extreme environments.

If ecologists or environmental scientists are talking about desert ecological research, then almost everyone is thinking about specific desert flora, fauna, or desertification itself as a consequence of climate change, or sand dune-triggered disasters. In fact, the importance of ecological research in deserts is far more general and broader.

We hope that our book will be interesting and useful for researchers, lecturers, students and anybody interested in this field.

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