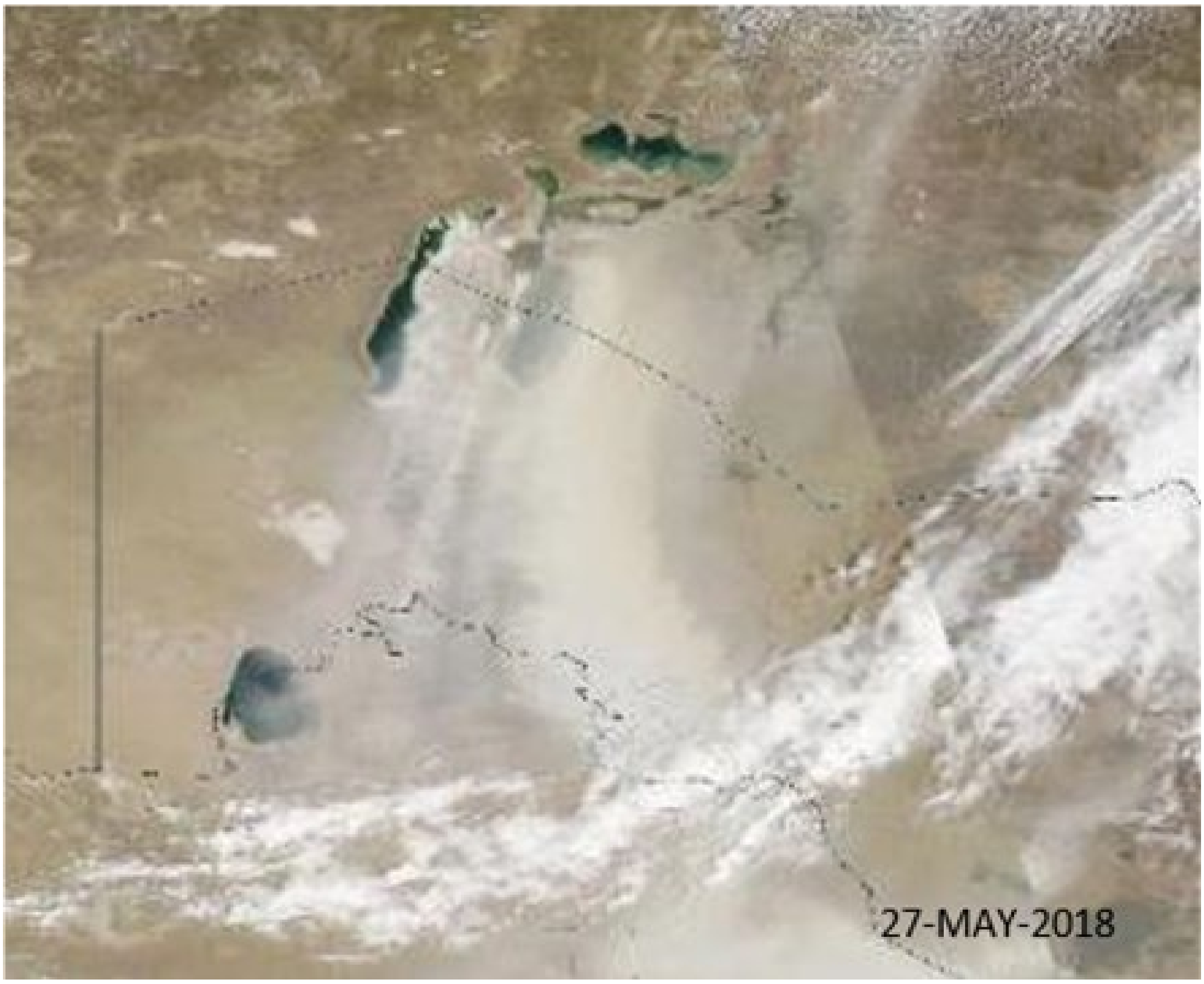
THE WORLD BANK
IBRD • IDA | WORLD BANK GROUP
Europe & Central Asia

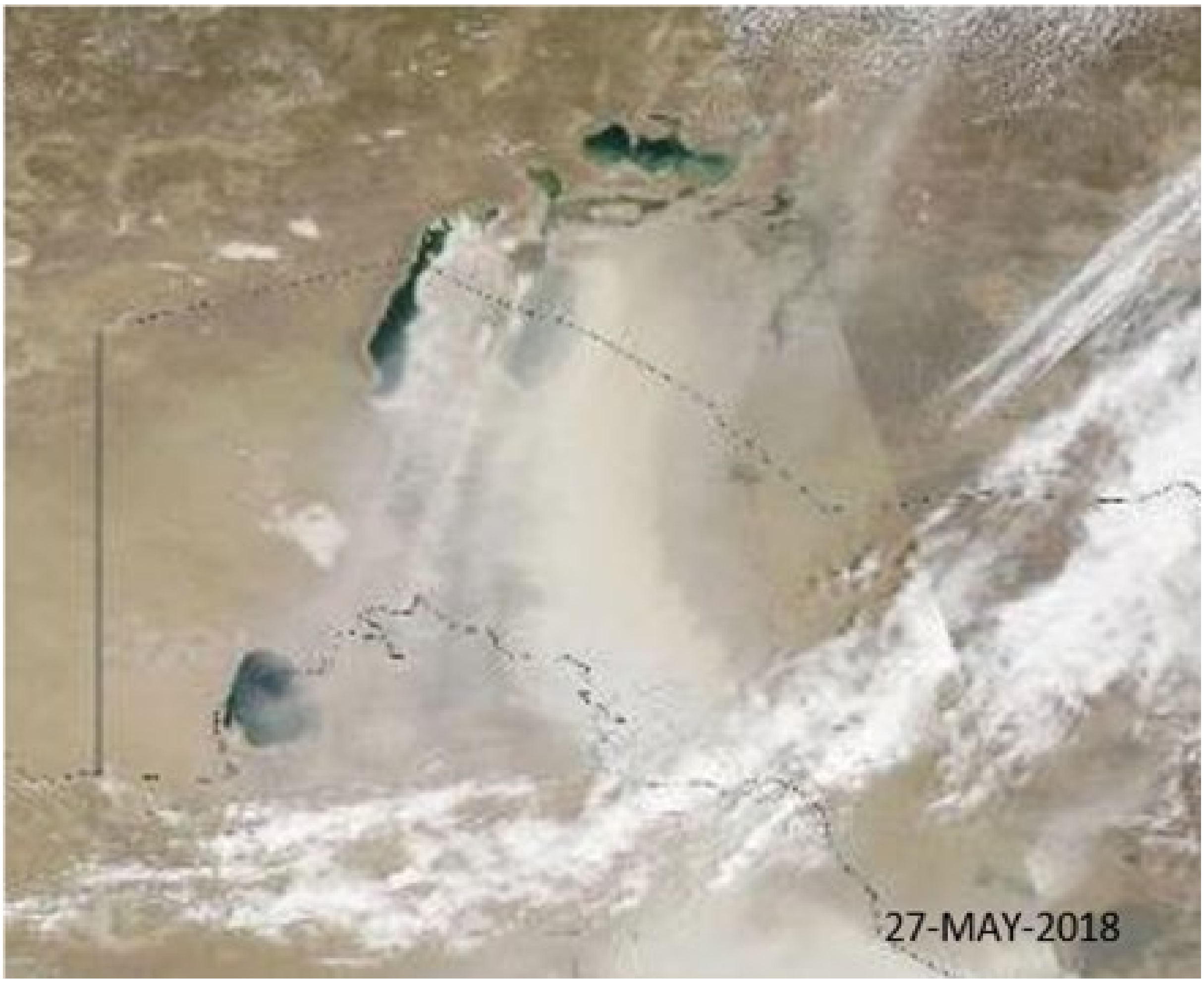
WAVES

RESILAND CA+
RESILIENT LANDSCAPES PROGRAM
PROGREEN

The Value of Landscape Restoration in Uzbekistan to Reduce Sand and Dust Storms from the Aral Seabed

August 2021





https://worldview.earthdata.nasa.gov/.

Cover photo: Panorama view of the Aral Sea from the rim of the Ustyurt Plateau near Aktumsuk Cape, Karakalpakstan, Uzbekistan.

.

Contents

Contents

List of Figures

List of Tables

List of Maps

Acknowledgments

This study was led by Paola Agostini (Lead Natural Resources Management Specialist, the World Bank), Elena Strukova Golub (Senior Environmental Economist, the World Bank) and Akmal Akramkhanov (Senior Scientist, International Center for Agricultural Research in the Dry Area (ICARDA), Uzbekistan). The team included Nodira Akhmedkhodjaeva (Environmental Specialist, the World Bank) and Camilla Sophie Erencin (Economist Consultant).

The study was carried out by Stefan Strohmeier (ICARDA, Jordan), Yigezu A. Yigezu (ICARDA, Egypt), Mira Haddad (ICARDA, Jordan), Timon Smeets (Utrecht University, Netherlands), Geert Sterk (Utrecht University, Netherlands), Claudio Zucca (University of Sassari, Italy), and Abduvokhid Zakhadullaev (Uzbekistan State Committee on Forestry).

This study benefitted from the valuable insights and comments of the following peer reviewers: Juan Pablo Castaneda Sanchez (Environmental Economist, the World Bank), Stephen Ling (Lead Environmental Specialist, the World Bank), and Feras Ziadat (Land Resources Officer, Food and Agriculture Organization). The team would like to thank Kseniya Lvovsky (Practice Manager, Environment, Natural Resources, and Blue Economy for Europe and Central Asia Region, the World Bank), Urvashi Narain (Lead Economist, the World Bank), and Raffaello Cervigni (Lead Environmental Economist, the World Bank) for their invaluable guidance.

The World Bank team would like to express its sincere gratitude to government officials: Sobirjon Umarov and Abror Nozimov (Uzbekistan State Committee on Forestry), Tabassumkhon Ruzmetova (Karakalpakstan Ministry of Health), and other experts from Uzbekistan for their insights and generous cooperation during the study. Special thanks go to the participants of the January 29, 2020 Inception Workshop hosted by the Uzbekistan State Committee on Forestry; representatives of regional institutions, ministries, and committees engaged in forest management, tourism, environment, and public health administration; and to development partners for their valuable comments and recommendations.

This study was supported by Wealth Accounting and the Valuation of Ecosystem Services (WAVES) and PROGREEN, the Global Partnership for Sustainable and Resilient Landscapes. WAVES is a World Bank-led global partnership that aims to promote sustainable development by ensuring that natural resources are mainstreamed in development planning and national economic accounts. PROGREEN is a World Bank partnership program that supports countries' efforts to improve livelihoods while tackling declining biodiversity, loss of forests, deteriorating land fertility, and increasing risks such as uncontrolled forest fires, which are xacerbated by a changing climate.Support to the team provided by Grace Aguilar, Linh Van Nguyen, and Nigara Abate is gratefully acknowledged.

All data of the Karakalpakstan Ministry of Health cited in this study was obtained with support from the Uzbekistan State Committee on Forestry.

Acronyms and Abbreviations

AAP	Ambient Air Pollution
AOD	Aerosol Optical Density
BCR	Benefit to Cost Ratio
COP	Conference of the Parties
COPD	Chronic Obstructive Pulmonary Disease
DALY	Disability Adjusted Number of Life Years
DISC	Data and Information Services Center
ESA	European Space Agency
GDP	Gross Domestic Product
GMAO	Global Modeling and Assimilation Office
ha	hectare
IASA	Institute of Accelerating Systems and Applications
ICARDA	International Center for Agricultural Research in the Dry Areas
IHD	Ischemic Heart Disease
ISRIC	International Soil Reference and Information Centre
LC	Land Cover
LC	Lung Cancer
LRI	Lower Respiratory Illness
MERRA-2	Modern-Era Retrospective Analysis for Research and Applications, Version 2
MODIS	Moderate Resolution Imaging Spectroradiometer
m/s	Meter per Second
NASA	National Aeronautics and Space Administration
NCA	Natural Capital Accounting
NDVI	Normalized Difference Vegetation Index
NPV	Net Present Value
$PM_{2.5}$	Particulate Matter with a diameter of less than 2.5 μm
PM_{10}	Particulate Matter with a diameter of less than 10 μm
PV	Present Value
Ppm	Parts per million
RAMS	Regional Atmospheric Modeling System
SDS	Sand and Dust Storms
SLL	Statistical Lives Lost
SPEI	Standardized Precipitation Evapotranspiration Index (drought index)
TEB	Total Economic Benefits
TEC	Total Economic Cost
T2D	Diabetes Mellitus Type 2
UNCCD	United Nations Convention to Combat Desertification
US EPA	The United States Environmental Protection Agency

VSL	Value of Statistical Life
WAVES	Wealth Accounting and the Valuation of Ecosystem Services
WB	The World Bank
$\mu g/m^3$	Microgram per cubic meter

Currency Equivalents

Exchange rate for 2019 used in calculations
Currency unit = Soum (UZS)
UZS 1.00 = US$ 0.0001
US$ 1.00 = UZS 8,851

Executive Summary

Central Asia experiences frequent sand and dust storms (SDS), which have been made worse by human activity. Formed from the dry Aral Seabed and with an estimated area of 60,000 km^2, the Aralkum Desert with its high salt concentration has become an additional source of SDS. This has not only transformed the surrounding environment, triggering soil degradation and desertification processes, but also resulted in poor health and the loss of livelihoods. Immediate areas affected by the Aral Sea disaster are in Kazakhstan and Uzbekistan, with lasting impacts experienced by communities near the former seashore, including the Republic of Karakalpakstan and Khorezm region in Uzbekistan. The landscape's assets, all within 500 km of the former seashore, consist of dry rangelands, irrigated agriculture areas, water bodies of various size, and human settlements.

Rehabilitation of the land is crucial to reduce the negative effects of SDS. Without intervention, the exposed seabed experiences primary succession, with native vegetation growing on different sites, depending on the soil salinity, texture, and waterlogging. This change is slow, spontaneous, and contributes little to reducing erosion; however, the planting of adapted shrub and tree species to reduce the negative effects of SDS is a promising choice that the government supports. Such measures also address Uzbekistan's pledge to the Bonn Challenge, a global initiative to restore degraded and deforested landscapes. The target—to restore 500,000 hectares (ha) by 2030—was actually met by 2020.[1] Despite such success and plans to continue planting on a larger scale, restoration results will depend on the survival rate of planted species and the maintenance of the established afforested areas beyond 2030.

The main objective of this study is to provide an economic analysis of the benefits of afforestation of the former Aral Seabed in Uzbekistan. To establish economic benefits, the best vegetation-based rehabilitation scenarios are defined. Then, the impact of wind erosion on ecosystem services is estimated by modeling sediment movement and dust production under each rehabilitation scenario. Finally, costs related to SDS in the Aral Seabed, and the potential benefits of vegetation-based rehabilitation scenarios, are estimated.

Based on wind erosion modeling results, this study measures soil retention ecosystem services in the former Aral Seabed in Uzbekistan. The event-based biophysical modeling estimates wind erosion, associated sediment movement, and the resulting dust production. The benefit of rehabilitation is estimated by combining representative wind speed classes with various scenarios. Negative impacts on soil carbon (on-site impacts) and human health and crop production (off-site impacts) under current Aral Seabed desertification conditions are also estimated. Foregone benefits are evaluated, including carbon that could have been sequestered in vegetation above and below the ground, as well as forage and wood that could have been harvested under best-practice scenarios. Finally, the potential benefits of different intervention scenarios are evaluated over a period of 20 years.

To understand the value of soil retention ecosystem services, several scenarios of landscape restoration are considered. Baseline scenarios represent current dry seabed conditions, while two rehabilitation options represent potential out-planting of native shrub and tree species. The scenarios facilitate the emergence of native vegetation (e.g., grasses) through shelter of primarily out-planted species or natural regeneration and succession. Simulation of SDS events with the scenarios demonstrates clear effects of shrub and tree vegetation—with the additional effect of grasses—on reducing erosion and sediment suspension.

The impact of SDS on on-site and off-site ecosystem services is analyzed, including several factors as a function of the distance from the Aralkum Desert. The empirical model is used to estimate the Aralkum's contribution to the concentration of particulate matter with a diameter of less than 2.5 μm ($PM_{2.5}$) and to calculate economic impacts of SDS originating from the dry seabed. For each scenario, vegetation-

---

[1] https://www.bonnchallenge.org/resources/spotlight-uzbekistan

specific information is identified, including plant height, quantity, breadth, and porosity. The soil organic carbon stock is estimated from global and published datasets. First, the on-site quantities and values of ecosystem services (i.e., soil carbon, carbon from above and below biomass, wood, and forage) being lost are determined. Second, the quantities and values of the specific ecosystem services that have been lost off-site are estimated, namely: 1) the number and economic value of statistical lives lost (SLL) and 2) the volumes and values of production of different crops lost due to associated SDS.

Key Findings

SDS from the Aralkum are causing Karakalpakstan to lose $44.2 million/year—equivalent to 2.1% of its Gross Domestic Production (GDP). Under existing conditions and assuming a planning period of 20 years, inaction will cost Karakalpakstan approximately $844 million. Of that total, 83% is on-site losses and forgone on-site benefits of ecosystem services and the remaining 17% is off-site losses.

Continued current practices would result in the loss of on-site benefits averaging $32.6 million/year—equivalent to 1.54% of Karakalpakstan's GDP. Simulation results show that 2.1 million tonnes of soil carbon valued at $207 million has been lost due to SDS from the restorable part of the Aralkum Desert in Uzbekistan. Also, a total of 2 and 2.7 million tonnes of carbon (valued at $108 million and $146 million, respectively) that could have been sequestered in the vegetation above and below the ground has been forgone. Finally, forage and wood that could have been harvested if the best course of action was taken represent a benefit loss of $111 million and $80 million, respectively. Therefore, over a period of 20 years, the total loss of on-site benefits is approximately $652 million.

SDS generated by the former Aral Seabed lead to off-site effects due to wind erosion exposure, including health impacts and crop production losses averaging $11.6 million/year. Off-site production losses for all major crops grown in Karakalpakstan are estimated on average at $9.9 million/year, equivalent to approximately 0.45% of Karakalpakstan's GDP. Dispersion modeling results show that the contribution of the Aralkum Desert to total ambient air pollution (AAP) reduces greatly over distance. The annual number of SLL attributable to SDS is estimated to be between 13 and 29 in this sparsely populated area. This leads to an annual welfare loss of approximately $1.7 million/year, equivalent to 0.08% of Karakalpakstan's GDP. Therefore, over a period of 20 years, the total loss of off-site benefits is approximately $192 million.

Landscape restoration interventions in the Aralkum can prevent ecosystem services losses and generate additional benefits of about $39 million/year—equivalent to 1.9% of Karakalpakstan's GDP. Interventions with planting of different vegetative covers at various levels of success rate in terms of the final percentage of total area covered by shrubs and/or trees were analyzed. The best course of action—simultaneous planting of trees and grass—would reduce the number of SLL attributable to SDS originating from the dry Aral Seabed by 12 on average; with a value of $1 million. This would represent a 58% reduction from the current scenario—equivalent to 0.05% of Karakalpakstan's GDP. In addition, the simultaneous planting of trees and grasses would reduce on-site benefit losses. Landscape restoration would also prevent crop production losses of approximately $5.5 million—equivalent to 0.3% of the GDP. The estimated benefit-to-cost ratio (BCR) is, on average, 1.49 for the present values of benefits and costs of different interventions.

Ecosystem service benefits from restoration projects in Uzbekistan provide far greater value than the economic and financial benefits of increased production if the appropriate restoration methods are applied. This study informs Uzbekistan's resilient forest restoration program by estimating a value of major direct and indirect incremental benefits of afforestation projects. Overall, afforestation in Uzbekistan has proven to be economically viable. It is an important part of the green growth strategy that supports climate goals and economic development. The valuation of ecosystem services benefits, both local and global, contributes to dialogue and analysis of climate targets in a context of broader development (e.g., priority of economic recovery, jobs, etc.) that are supported by the Uzbekistan State Committee on Forestry and Ministry of Finance. The valuation of ecosystem services benefits also informs Uzbekistan's ongoing legal and regulatory reform (Environmental Code, Forest Strategy, regulation of greenhouse gases) by providing quantitative measurements and thresholds for financing the country's afforestation activity.

1 Introduction

Globally, sand and dust storms (SDS) are mostly considered a natural phenomenon. The Global Assessment of SDS (UNEP, WMO, UNCCD, 2016) reviewed scientific estimates of the relative contribution of human activity to current levels of global dust emissions and indicated 25% as the most likely estimate. Desertification and land degradation are typical drivers of human-caused SDS (UN, 2001; UNESCAP, 2018).

The Aralkum Desert, the seabed of the former Aral Sea, is a relatively new addition to global hotspot sources of SDS with high salt concentration. Although Central Asia has been historically characterized by a high frequency of SDS, due to the presence of the Kyzylkum and Karakum Deserts, human activity has exacerbated the frequency and intensity of SDS through *unintentional* creation of a vast area of land dominated by saline soils (Solonchaks) and bare areas. The rapid transformation of the Aral Sea into the Aralkum Desert in the course of a few decades is staggering. The Aralkum Desert's area covers around 60,000 km^2, of which 70% is salt desert (Breckle and Geldyeva, 2012).

Consequently, the loss of sea not only has transformed the surrounding environment—triggering enhanced degradation and desertification—but also resulted in the loss of livelihoods, malnutrition, poor health, and migration issues. The resulting effect is thus not limited to environmental degradation, but also causes economic and social consequences. Considering the recent predictions of the temperature rise in Central Asia above global mean values (World Bank, 2014), ongoing desertification and socio-economic pressure on communities in the Aral Sea Basin might be worsened. Studies indicate that annual losses of agricultural production from soil salinization in Central Asia are estimated at $2 billion (World Bank, 1998), which could also translate into losses of soil carbon through reduced plant growth. The annual costs of rangeland degradation due to poor management are estimated at $4.6 billion between 2001 and 2009 (Mirzabaev et al., 2015).

The Aralkum source for SDS covers 20,000–30,000 km^2 while raised, suspended, and transported salt and dust particles reach the surrounding areas occupying over 500,000 km^2 (Groll et al., 2013; Orlovsky and Orlovsky, 2001). The chemical composition of sand and dust originating from the Aralkum is dominated by higher salt concentrations compared to those deriving from the Kyzylkum Desert (Aslanov et al., 2013). Spatially, the distribution of salt and dust transfer occurs in the south and southwest directions (Groll et al., 2013; Orlovsky and Orlovsky, 2001), affecting ecosystems, irrigated and populated areas of Karakalpakstan and Khorezm province in Uzbekistan as well as Dasoguz in Turkmenistan.

Since the Aral Sea is in a depression, receiving discharge from Amudarya and Syrdarya Rivers irrigating and draining vast areas, numerous reports suggest that accumulated sediments have high concentrations of toxic elements (Micklin, 1988; UNEP, WMO, UNCCD, 2016). For example, Thenardite—suspended salt residues in the air—are suspected to be one of the main causes of lung disease in the region (Letolle et al., 2005). However, few studies analyze the direct effect of salt and dust from the Aralkum on human health, despite the high rates of anemia, lung cancer, respiratory and diarrheal diseases, heart attack, hepatitis, birth defects and higher blood level of toxins among population in the adjacent region (Crighton et al., 2011). The inter-relationships between the environment and production, human health and rural livelihoods are complex to estimate and require proper attention and investigation.

There are various rehabilitation options to reduce the negative effects of SDS. Tree plantations, indigenous or adapted, to the region offer improved ecosystem services via soil and water retention, preventing polluted dust from being transported. Several initiatives have been launched and tested in distinct parts of the former Aral Seabed under international projects and supported by the local government.

In 2017, given the relevance of land degradation and desertification to SDS, the 13th Session of the United Nations Convention to Combat Desertification (UNCCD) Conference of the Parties (COP) adopted Decision

31/COP.13[2] on SDS and invited countries to use the UNCCD Policy Advocacy Framework to address the impact of SDS. Building on earlier successful experiences with restoration and rehabilitation, along with the need to mitigate SDS effects, Uzbekistan joined the Bonn Challenge,[3] a global initiative to restore degraded and deforested landscapes. In 2018, it pledged to restore 500,000 ha by 2030 through the Astana Resolution.[4] That target was achieved by 2020.[5]

Objectives of the Study

The objective of this study is to estimate economic benefits attributed to afforestation of the former Aral Seabed in Uzbekistan. Proper estimation and categorization of economic benefits associated with each scenario of landscape restoration enables the Government of Uzbekistan and local authorities to allocate limited resources in an efficient way, supporting promising rehabilitation techniques and practices.

[2] https://www.unccd.int/sites/default/files/sessions/documents/2019-08/31COP13_0.pdf
[3] https://www.bonnchallenge.org/about
[4] https://www.bonnchallenge.org/resources/ministerial-roundtable-forest-landscape-restoration-caucasus-and-central-asia-summary
[5] https://www.bonnchallenge.org/resources/spotlight-uzbekistan

2 Review of Ecosystem Services in SDS Context

The review and classification of literature focused on SDS generated by the Aral Seabed helped to categorize the impacts according to the Natural Capital Accounting (NCA) approach.[6] The SDS impacts were grouped according to two categories: impact on on-site and off-site ecosystem services (Table 2.1). These services present actual or potential annual flows of goods and services provided by ecosystems in the targeted area to people (via economic production or directly to individuals and society)[7]. The annual flows are estimated both under the current scenario and alternative landscape restoration scenarios.

Table 2.1: Impact on Ecosystem Services Associated with Different Intervention Scenarios, Categorized According to the NCA Approach.

	On-Site	Off-Site
Provisioning Services	Potential of timber, firewood, and forage production	Crop production
Regulating Services	Soil erosion: soil loss, degradation or pollution; and potential climate regulating services (including soil carbon and biomass)	Potential climate regulation services
Health Impact		Disease and mortality costs

Source: Based on Wealth Accounting and the Valuation of Ecosystem Services (WAVES)

The SDS impacts affecting ecosystem services can be observed both on-site and off-site. The distinction between these effects cannot be rigid because of the continuity of spatial scales involved. Inside the source area (on-site), where both soil particle detachment and entrainment take place, all types of impacts can be observed, associated with erosion (soil loss, undermining of structures, etc.), transport (air quality, visibility, etc.), or deposition (sand encroachment) of particles. Moving away from the source area (off-site), depending on the distance and wind speed, as well as wind direction, various types of impacts can still be observed. For example, at regional-to-global scale, impacts caused by transport and deposition of very fine particles can be observed.

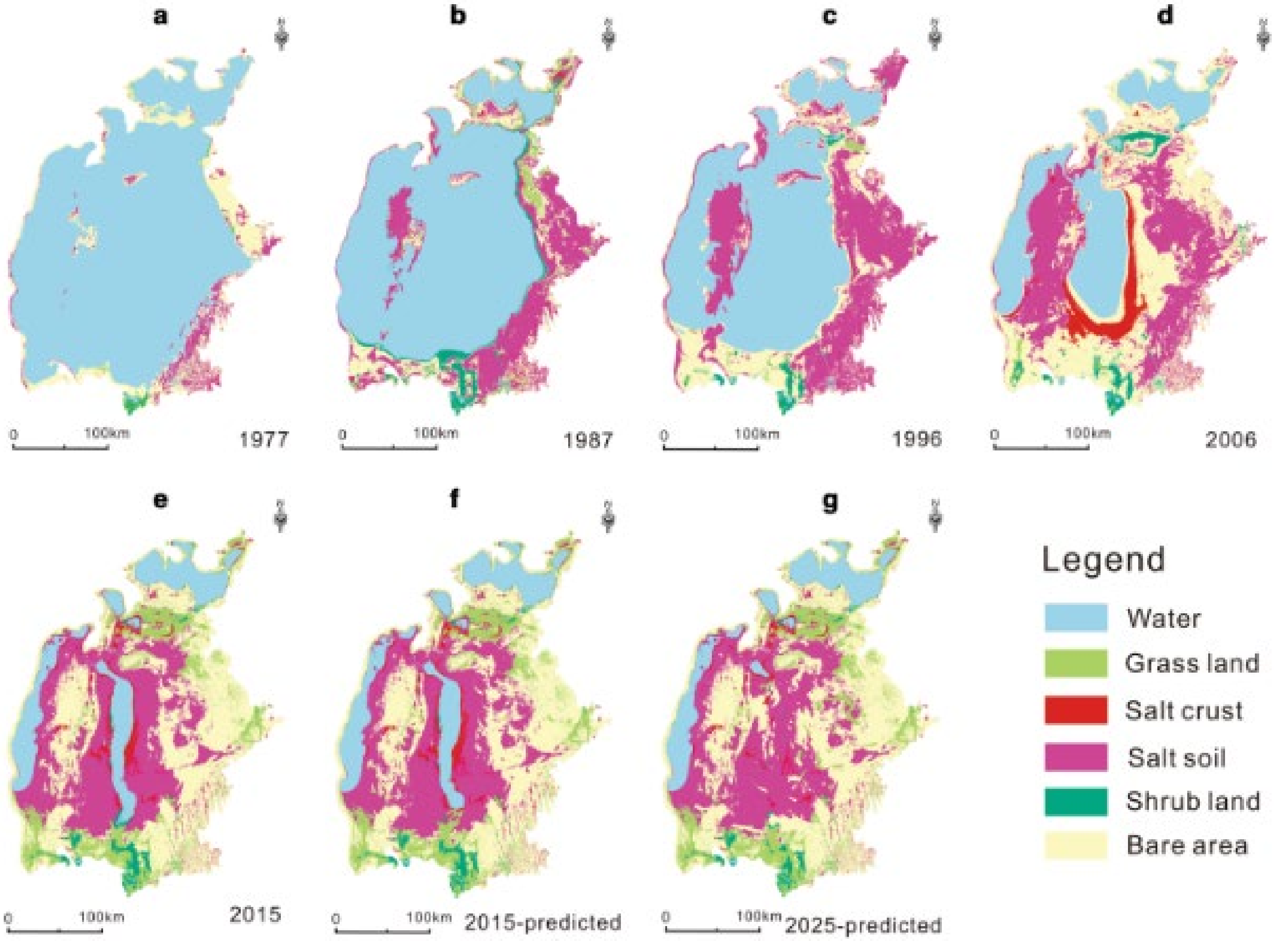
2.1. Impacts on Local Soil and Vegetation, and Dust Emission

The desiccation of the Aral Sea exposed the seabed, forming large bare areas of saline soils (Figure 2.1) and creating a sand and salt desert ecosystems (the new “Aralkum” Desert). Their characteristics are influenced by the variable and complicated geological and geomorphological structure of the desiccated seafloor.

[6] The World Bank Group leads the Wealth Accounting and the Valuation of Ecosystem Services (WAVES) partnership to advance NCA internationally. The NCA is based on the Millennium Ecosystem Assessment (Reid et al.,2005), a major assessment of the human impact on the environment which popularized the term ecosystem services.

[7] Impacts could be positive or negative, for soil erosion cost and health/lost crop cost associated with SDS.

Figure 2.1 Desiccation and Land Cover Change of the Aral Sea During 1977–2015



Source: Shen et al. (2019).

According to Löw et al. (2013) the sandy surfaces and the salt-affected soils increased by more than 36% between 2000 and 2008. Indoitu et al. (2015) state that exposed heavy takyr, takyr-like and Solonchak surfaces have high potential to be a source of severe SDS: the most active emission site consisting of sands (75%), Solonchaks (17%) and takyrs/takyr-like soils (8%) which are heavy clay. Most of the SDS events in the Aral Sea basin originate from the north-eastern Aral Seabed area, usually under action of winds from the east (57%) and more generally from eastern areas (80%). Dust plumes often reach lengths of 150 km to more than 600 km.

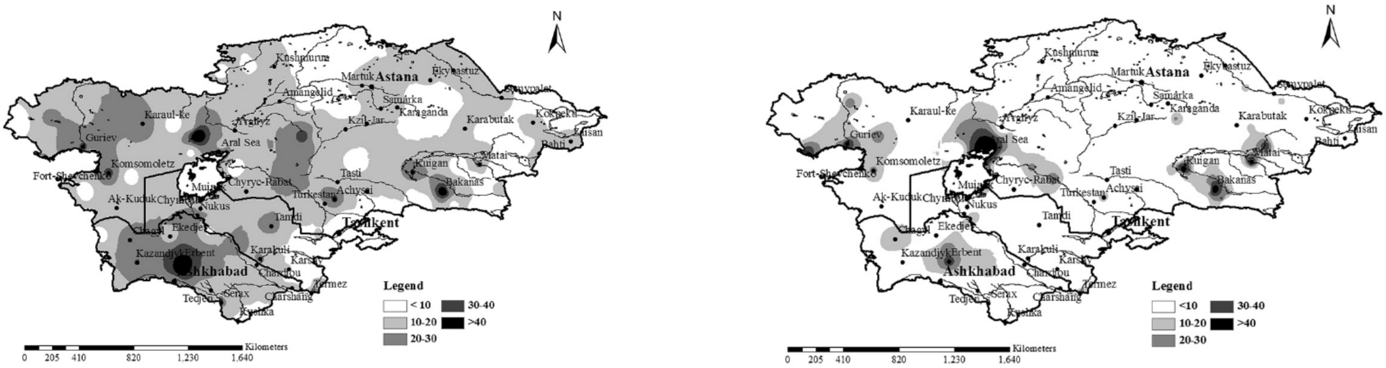
Semenov (2012) developed a physical model to evaluate the amounts of aerosols transported from the desiccated seabed of the Aral Sea. Evidence shows that the increase in size of the desiccated seafloor contributes to higher amounts of smaller size (less than 10 μm) particles, with higher salt content. The small size increases the distance over which particles are transported by wind. The salt-dust clouds can be up to 400 km long, while finer particles can travel up to 1,000 km away.

Bare sediments start to be taken over by native vegetation species, with colonization patterns and rates depending on salinity and texture of the newly formed soils (Dimeyeva, 2007; Wucherer et al., 2012a). This has transformed the Aralkum into the largest area worldwide where primary succession is taking place (Wucherer et al., 2012a). Although the rate of spontaneous vegetation cover is not sufficient to reduce dust generation significantly, the observed process poses a great ecological interest and a learning opportunity for restoration scientists.

2.2. Impacts on Regional Dust Emission and SDS Occurrence

Dust generation activated by the exposed seabed has transformed the Aral Sea region into a regional SDS hotspot. Indoitu et al. (2012) analyzed all SDS events in Central Asia between 1936 and 2005. The northern Aral Sea region became the regional hotspot with more than 40 SDS days/year after the 1980s, while decreasing trends were most obvious for Karakum Desert, where the number of SDS declined from an average of 30 days/year to less than 20 (Figure 2.2). Other spatial changes occurred in the Northern Caspian Deserts, showing a shift of few hundred kilometers to the east. Orlovsky (2011) reports the Kyzylkum Desert and the south Balkhash Lake area underwent an important surface reduction of major source areas. This was largely due to the recovery of ecosystems instigated by reduced human activities in the region post-1980s and partly by the decreasing trends of SDS frequencies registered worldwide. Accordingly, the Aralkum dynamics contrasted the regional ones. The diffusion of dust originating from the Aral Sea Basin showed strong increasing trends of aerosol indices after 2005 until 2013, associated with the continuous decrease in water level (Ge et al., 2016).

Figure 2.2 SDS Occurrence in Central Asia During 1936–1980 (Left) and 1980–2000 (Right)



Source: Indoitu et al. 2012.

2.3. Impacts on Air and Ecosystems: Dust Loads and Dust Deposition

The transport and fall-out of dust particles generated from the Aral Sea region affects air quality of the downwind regions. Simulation modeling based on MODIS[8] and AERONET[9] data for the period of April 2008–July 2009 showed that dust was the largest component of particulate matter (both $PM_{2.5}$, up to 2.5 μm size, and PM_{10}, up to 10 μm size) mass in Central Asia in all seasons except winter, as well as the driver of seasonal PM and AOD (Aerosol Optical Density) cycles (Kulkarni et al., 2015).

Based on all SDS events during May–October 2000 and monthly dust deposition at 16 sites in Karakalpakstan, Wiggs et al. (2003) observed extremely high monthly fine PM concentrations. Concentration levels were comparable to the United States Environmental Protection Agency (US EPA) quality standards of 150 μg/m^3 in a 24-hour period and 50 μg/m^3 as yearly average, with deposition rates as high as 2.5 tonnes/ha. High levels of dust deposition were observed throughout the country in the summer months, with particularly high rates of deposition in the north close to the shore of the former Aral Sea.

For seven sites located in western and central Uzbekistan (Moynaq, Jaslyk, Takhiatash, Yangibozor, Beruniy, and Buzubay) Aslanov et al. (2013) found average dust deposition rates during the 2007–2010 period were five to six times higher than during 1982–1995. On the other hand, they also found a lower average deposition rate near the Aralkum than near the Kyzylkum (e.g., 450 kg/ha per month in Moynaq and 1,200 kg/ha per month in Buzubay).

---

8 Moderate Resolution Imaging Spectrometer (MODIS). https://modis.gsfc.nasa.gov/
9 AErosol RObotic NETwork (AERONET) project. https://aeronet.gsfc.nasa.gov/

2.4. Dust Salinity

In the Aral Sea region, white or "salty" storms first appeared with the intensive irrigation development in the 1960s. Large areas of newly salinized lands and human-caused saline soils (Solonchaks) formed, with unusually strong SDS first recorded in 1975.

Orlovsky and Orlovsky (2001) report that soils formed on sandy and sandy-loam exposed marine sediments have high sulfate-chloride and chloride-sulfate salts that may reach 8–10%, corresponding to about 2,200 tonnes/ha in the aeration zone of the soil. They also report that the total amount of deposited aerosols in the southern Aral Sea zone, studied between 1982 and 1991 at 43 sites, was 1.5–6.0 tonnes/ha and included about 170–800 kg/ha of soluble salts, with maximum values of up to 1,600 kg/ha in the dried seabed of the Aral Sea. This value was lower (150–300 kg/ha) in the irrigated lands of Karakalpakstan. The salt content in deposited aerosols in the Amudarya delta was estimated at 5–6%, and up to 20–30% in areas close to Solonchaks soils.

Groll et al. (2019) analyzed dust deposition samples collected during 2003–2012 from 23 meteorological stations in four regions of the Aral Sea basin (Aralkum, Khorezm, Karakum, and Kyzylkum). They observed that the majority (86–98%) of the material deposited at 3 m height in the study area was part of the PM_5 group (fine silt and clay particles; <0.0063 mm) and that the Aralkum dust samples were characterized by a much higher concentration of sulfites compared to the Karakum and Kyzylkum (2,365 parts per mile (ppm) vs. 232 ppm and 512 ppm). Khorezm also showed high sulfite content (1,681 ppm) and had the highest concentration of phosphorus pentoxide (1,857 ppm compared to 1,074 ppm in the Aralkum 866 ppm in the Karakum and 465 ppm in the Kyzylkum). The high concentrations of phosphorus in Khorezm and the Aralkum samples reflected the strong human impact of local agricultural dust sources (Khorezm) and the accumulation of agrochemicals in the Aral Sea sediments.

2.5. Impacts of the Aralkum Dust on Human Health

Health hazards emanating from SDS receive limited attention despite their cumulative effects on society (Middleton et al., 2019). An increasing body of literature confirms that $PM_{2.5}$ contributes to cardiovascular and respiratory diseases, and consequently can lead to premature death (Lelieveld et al., 2020). Regional evidence, however, linking SDS caused air pollution and health burden is lacking.

Few studies covering the Aral Sea region acknowledge the health risk due to high dust concentrations (Opp et al., 2017). A literature review compiled by Crighton et al. (2011) on the effects of the Aral Sea disaster on children's health mentioned 26 peer-reviewed articles and four major reports published between 1994 and 2008. Anemia, diarrheal diseases, and high body burdens of toxic contaminants were identified as significant health problems for children in the area. These health issues are associated either directly with the environmental disaster or indirectly via the deterioration of the region's economy and social and health care services.

Adult and children respiratory diseases studied in Turkmenistan (O'Hara et al., 2000) were a major cause of illness and death among all age groups but accounted for 50% of all reported illnesses in children. Conversely, in a study conducted in Karakalpakstan (Bennion et al., 2007; Wiggs et al., 2003), respiratory health surveys of children (aged 7–11) did not show a significant relationship between respiratory health problems and proximity to dust sources. Other studies showed that populations living near the former Aral seashore suffer from the worsening of several diseases (Kunii et al., 2003). A significant increase of cough and wheezing, lower forced vital capacity, and restrictive pulmonary function closer to the shore were prevalent in the area. Cancer cases (all cancer types, 2003–2014) around the north of the Aral Sea in Kazakhstan were 1.5 times more frequent compared to distal areas, due to higher nickel and cadmium levels (Mamyrbayev et al., 2016). Although clear evidence for the link between dust exposure and respiratory functions might be lacking, these studies unequivocally confirm the impact of the Aral Sea disaster on public health, underlining the knowledge gaps and the need for further specific research.

2.6. Impacts of the Aralkum SDS on Economic Activities

Economic impacts of SDS generated from the Aralkum Desert appear poorly explored in publications. INTAS and RFBR (2001) provide an overview of actual economic impacts with cost estimations referring to the entire Aral Sea disaster, which only partly can be associated with SDS. The assessment is based on a multi-sector approach, addressing both land and water resources. Identified impacts are summarized in Table 2.2. The costs for the entire Aral Sea region were estimated at $100 million/year ($59 million for agriculture and $41 million for manufacturing and service industries).

Other papers address concurrent uses of water resources in the region and related impacts (e.g., availability of drinking water and irrigation water, crop yields, fishery, etc.). Orlovsky and Orlovsky (2001) report losses of cotton at 5–15% and rice yields at 3–6% resulting from dust. The salt content of rain is also reported to have increased to 100–150 mg/l compared to 30–100 mg/l in 1975. In the springtime, this rain creates salty crusts affecting seed germination and shortening the lifespan of supporting structures of high-voltage transmission lines. Additional finance to repair transmission lines in the Raushan-Beruniy of the Kungrad railway section in 1981–1990 increased to $15 million, and property damage as a result of power breaks raised expenditure to $9 million. As a result, total capital expenditures exceeded the budgeted investments 2.8 times for the same period.

Table 2.2: Recorded Economic Impacts of the Aral Sea Disaster

Sector	Issues	Costs, $ million
Fishery	Amount of fish catch in the Sea and adjacent lake systems reduced by 90%	28.57 (fishery and fish breeding) 9.0 fish industry)
Hunting	Muskrat habitats sharply diminished, resulting in lower muskrat numbers and decreased catch by hunting	4.0 (hunting) 18.0 (pelt processing)
Cane	Reduction of habitat for cane growing	12.6 (cane processing)
Irrigated Farming	From 1994–95, the used irrigated lands throughout the Aral Sea zone have reduced by 25%, causing reduced crop productions. The most affected crops were grain crops, rice, forage, maize, cotton, vegetables, and cucurbits	6.55 (crop production)
Rangeland	Decreased river runoff into the Amudarya Delta and drying of vast areas of former seabed resulted in an acute reduction of natural highly productive rangelands and hay-mowing areas affecting cattle breeding and sheep and goat numbers, particularly in the Tahtakupyr district	8.4 (cattle breeding)
Wool Production	Production of wool and Astrakhan pelts dropped to a half, driven by the drop in the number of sheep and goats and by the deteriorated conditions of pasture and rangelands	N/A
Tourism	The number of tourists attracted by hunting and fishing sharply decreased	11.16
Cost of Rehabilitation	Rapid withdrawal of coastline hampering rehabilitation activities in the coastal zone	N/A

Source: INTAS and RFBR (2001).

In addition to the direct costs, INTAS and RFBR (2001) report $17 million of indirect losses and $29 million associated with social losses, annually. Thus, total direct and indirect losses caused by the environmental disaster in the Aral Sea region amounted to $146 million/year. It is worth noting that this was quantified in 2001 when the level of impact on land and water resources was much lower.

2.7. Rehabilitation

Desiccation of the Aral Sea exposes large areas of dry seabed. Without human intervention, natural succession of the spatial sequence of land cover around the shoreline of the former Aral Sea can be summarized as follows: “water”>“salt crust”>“salt soils”>“bare areas and desert soils” (Löw et al., 2013). The water recession results in a quick build-up of extensive salt crusts directly adjacent to the sea. Then, most of these salt crusts convert into a series of different Solonchaks and takyr types (classified as “salt soil”) and subsequently, in some parts, into "bare areas" reflecting a gradual landscape evolution under arid conditions, with the transformation of salt soils into desert soils prone to erosion.

In parts of the Aralkum, under the leaching action of precipitations, natural desalinization of soils occurred within 4–8 years (Löw et al., 2013). While there is long-to-medium-term spontaneous recovery of vegetation (Dimeyeva, 2007; Wucherer et al., 2012b), the process is slow, and its success depends on many factors, including the intensity of wind erosion.

Active restoration options should provide a faster and more effective establishment of the vegetation cover and a subsequent reduction of generated dust. Additional direct benefits would include the establishment of other pastureland, which would contribute to improved livelihoods. Practices already tested in the region include planting of various native species adapted to salinity and drought conditions.

3 Methods

To meet the objectives of the study and estimate economic benefits from landscape rehabilitation scenarios, the following approach was applied: first, best-applicable vegetation-based rehabilitation scenarios for the Aral Seabed were defined. Second, the impact of wind erosion on ecosystem services was estimated by modelling a sediment movement and dust production under each scenario. Third, costs related to SDS in the Aral Seabed and potential benefits of vegetation-based rehabilitation scenarios were estimated. For further details on the methodology refer to 0.

Definition of suitable Aral Seabed rehabilitation approaches and scenarios

For the valuation of soil retention ecosystem services, several scenarios of landscape restoration are formulated. Scenario 1.1 Bare (-) and Scenario 1.2 Bare (+) represent the actual dry seabed conditions. Scenario 2.1 Shrub (-), Scenario 2.2 Shrub (+), Scenario 3.1 Tree (-), and Scenario 3.2 Tree (+) represent potential out-planting of native shrub and tree species. The scenarios with (+) include the emergence of native vegetation (e.g., grasses) facilitated through shelter of primarily out-planted species or natural regeneration and succession. The actual on-site environmental conditions, as well as the selected rehabilitation scenarios are described in Table 3.1.

Table 3.1: Scenario Overview: Degraded Status vs. Rehabilitation Through Shrub and Tree Plantations.

Environmental Condition	Scenario	Scenario Description (Vegetation Cover)	Expected Model Output (Notes)
1. Degraded (present condition)	Bare (-)	Bare: dried-up areas with no vegetation cover (highest vulnerability)	Present: most erosion susceptible scenario (worst case)
	Bare (+)	Bare, with marginal grass cover: older dried up areas with limited natural vegetation emergence (few bunch grasses)	Present: slightly reduced erosion susceptibility (checking the upper range of proneness to wind erosion)
2. Rehabilitated – Shrubs (shrub-based intervention)	Shrub (-)	Shrub cover: rehabilitated (Salsola or Atriplex) with out-planted shrubs without or with marginal natural recruitment (pure shrub out-planting effect)	Limited reduction of erosion: minimum of erosion resistance through human intervention (shrubs); the lower boundary of rehabilitation impact range
	Shrub (+)	Shrub cover: rehabilitated (Salsola or Atriplex), incl. recruitment and grasses; represents: out-planted shrubs with specific extent recruitment and grass cover	Reduction of erosion: checking the significance of human intervention vs. natural recruitment
3. Rehabilitated – Trees *(tree-based intervention)*	Tree (-)	Tree cover: rehabilitated (Saxaul); represents: out-planted trees with marginal or no natural recruitment (pure tree out-planting effect)	Limited reduction of erosion: minimum erosion resistance through human intervention (trees); the lower boundary of rehabilitation impact range and check vs. shrub intervention
	2. Tree (+)	Tree cover: rehabilitated (Saxaul) incl. recruitment and grasses; represents: out-planted trees with specific extent recruitment, shrub and grass cover (highest cover scenario)	Highest reduction of erosion through three different layers: 1) trees, 2) shrubs, 3) grasses (checking the significance of human intervention vs. natural recruitment)

(1) Wind erosion and dust assessment

The methodology for wind erosion and dust assessment in the dry Aral Seabed included several steps reflecting an analysis of the wind erosion biophysics. It included modeling of two major processes: 1) surface sediment movement through creeping and saltation, and 2) sediment suspension. Particle creeping and saltation can move substantial amounts of sediment and cause severe erosion and sediment accumulation in the target/source on-site area, yet hardly affect the off-site environment, as the predominantly coarse particles settle and deposit in nearby locations, as described by Smeets (2020).

On-site modeling: Large-scale modeling was undertaken to define the two on-site processes for different representative wind events—considering the thresholds of soil erosion (and consequential suspension), based on sensitivity and uncertainty analysis investigating the most common soil texture and initial soil conditions occurring in the dry Aral Seabed (Smeets, 2020). Wind speed analyses were performed based on three-hourly data from on-site meteorological stations, targeting daily wind events described through peak velocities (three hourly) and average wind speeds. Combined with fine resolution threshold analysis (i.e., threshold for substantial wind erosion) three different "storm classes" were defined according to their magnitude (erosivity) and occurrence probability (frequency). Simulation of the three classes, coupled with their statistical occurrence and per defined vegetation cover scenario (erodibility), enabled the estimation of on-site wind erosion dynamics and sediment balances.

Off-site modeling: The primary threat to off-site ecosystem services and health come from the suspension processes, which are a result of the saltation of coarser soil fragments releasing fine particles, often then lifted to higher elevations and transported over large distances. The off-site effects through 1) fine particle concentration in the air and 2) cumulative sedimentation processes were estimated using an empirical radial dispersion approach. The empirical model was manually adjusted using measured sediment accumulation data, available from the literature (partial manual calibration) and verified through selected event dust-atmospheric simulations using RAMS (Cotton et al., 2003; Pielke et al., 1992).

(2) Economic valuation of selected ecosystem services

In a first step, on-site and off-site SDS impacts are defined. Related to on-site effects, the value of soil that is eroded by wind is considered, as well as the opportunity cost of forest that could have been planted on the vast land of the Aralkum Desert—serving as an important carbon sink. For off-site impacts, health and crop production impacts are considered.

In the second step, four different rehabilitation scenarios are defined based on Table 3.1. Scenario 1 (which represents the current scenario) is a combination of Scenarios 1.1 and 1.2, i.e., 90% Bare (-) and 10% Bare (+). Scenario 2 is a combination of Scenarios 2.1 and 2.2, i.e., 50% Shrub (-) and 50% Shrub (+). Scenario 3 is a combination of Scenarios 3.1 and 3.2, i.e., 50% Tree (-) and 50% Tree (+). Finally, we define Scenario 4 as the best scenario, which assumes the full implementation of Scenario 3.2, i.e., 100% Tree (+).

Table 3.2: SDS Impact Indicators under Four Different Scenarios

Location of Impact	Impact	Scenario 1 90% Bare (-) and 10% Bare (+)	Scenario 2 50% Shrub (-) and 50% Shrub (+)	Scenario 3 50% Tree (-) and 50% Tree (+)	Scenario 4 100% Tree (+)
On-Site	Soil Carbon, t/ha				
	Carbon from biomass (above ground), t/ha				
	Carbon from biomass (below ground), t/ha				
	Firewood and forage				

Location of Impact	Impact	Scenario 1 90% Bare (-) and 10% Bare (+)	Scenario 2 50% Shrub (-) and 50% Shrub (+)	Scenario 3 50% Tree (-) and 50% Tree (+)	Scenario 4 100% Tree (+)
Off-Site	Cropland (all crops) yield + quality				
	Health				

In a third step, costs of SDS due to inaction are calculated using 1) district data on population size, crop areas, yield, and regional GDP for each area delineated as highly, moderately, or lightly affected by SDS from the Aralkum, and 2) prices of major crops, international carbon, and the Value of Statistical Life (VSL).[10] The total value of SDS impacts for defined on-site and off-site ecosystem services are the product of per-unit value of impacts and the population size/total area affected.

Table 3.3: Economic Valuation Methods Used to Estimate Costs of SDS in the Aralkum

	Impact	Valuation Method
On-Site	Soil Carbon	Social cost of carbon
	Carbon from biomass (above ground)	Converting total biomass of forest into carbon equivalents using standard conversion factors
	Carbon from biomass (below ground)	Converting total biomass of forest into carbon equivalents using standard conversion factors
	Provisioning services	Values of forage and firewood based on current prices
Off-Site	Crop yield	Crops lost due to SDS from the Aralkum times the average price of crops
	Health	Welfare loss of SDS induced $PM_{2.5}$ pollution using VSL

In a last step, benefits of alternative intervention scenarios are estimated as the difference in ecosystem services (annual flows) provided under rehabilitation scenarios and the base case scenario (Scenario 1) for upper bound, average, and higher bound outcomes of the rate of success for tree planting. The intervention with the highest net benefit is equal to the largest difference between the total economic benefit of the intervention and the total economic cost of implementing the intervention.

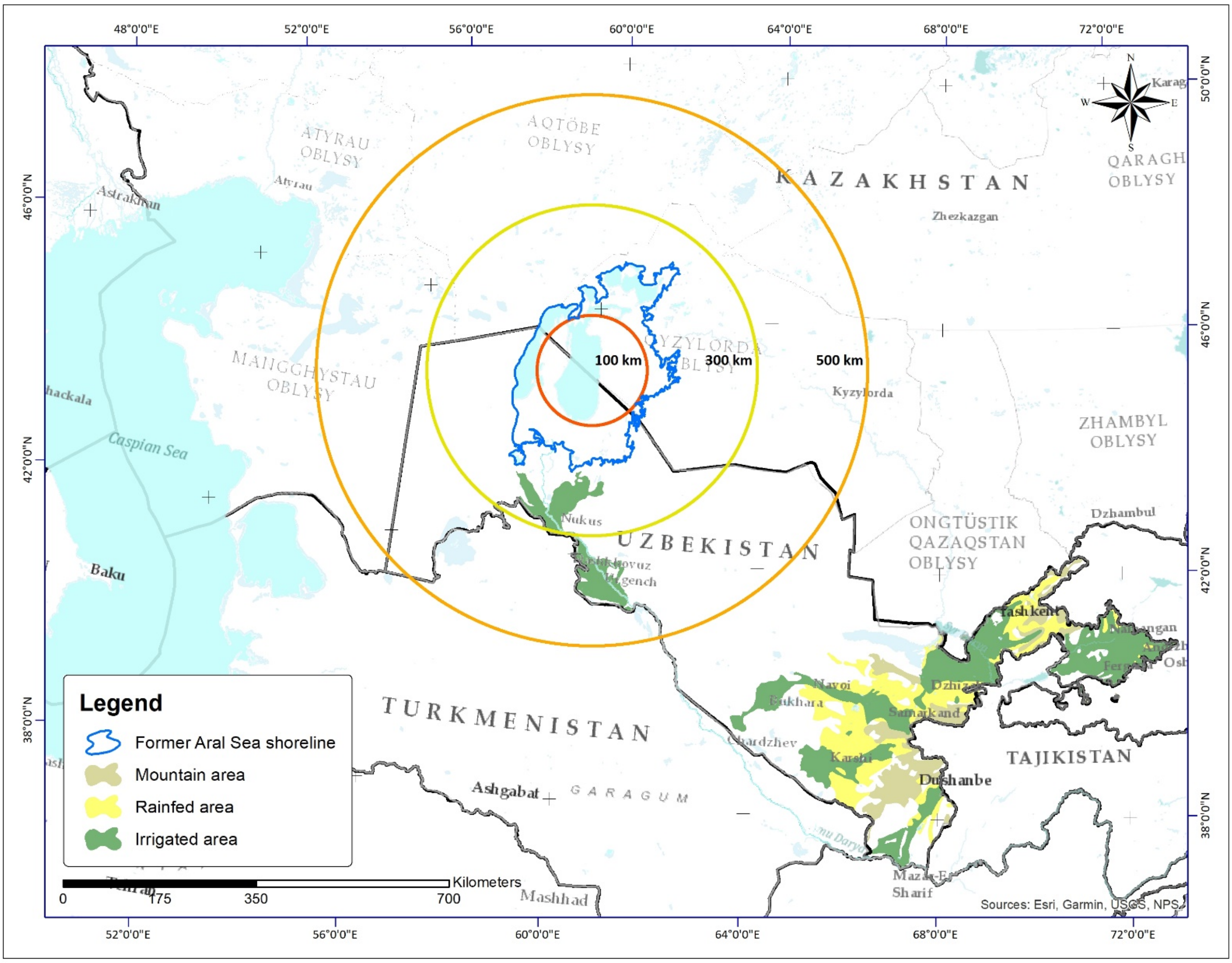
[10] Narain and Sall, 2016.

4 Results and Discussion

4.1. Analysis of Land Use/Cover Change

Assessed landscapes within proximity (100, 300 and 500 km radius) to the dry Aral Seabed (Map 4.1) consist of 1) dry rangelands, 2) irrigated agriculture areas, and 3) human settlements. A remote sensing-based study over the past two decades (2000–2020) allowed the investigation of degradation trends—comparing the assets' status to the areal extent of the changing Aral Seabed and other potential impacts, such as climate. This pre-study provided insights into the environmental (historical) context and was used as a basis and reference for SDS occurrence/pattern assessed through modeling.

Map 4.1 Literature-Based Estimated Areas of Off-Sites and SDS Impact in the 100 km (Severe Impact), 300 km (Medium Impact) and 500 km (Low Impact) Radius

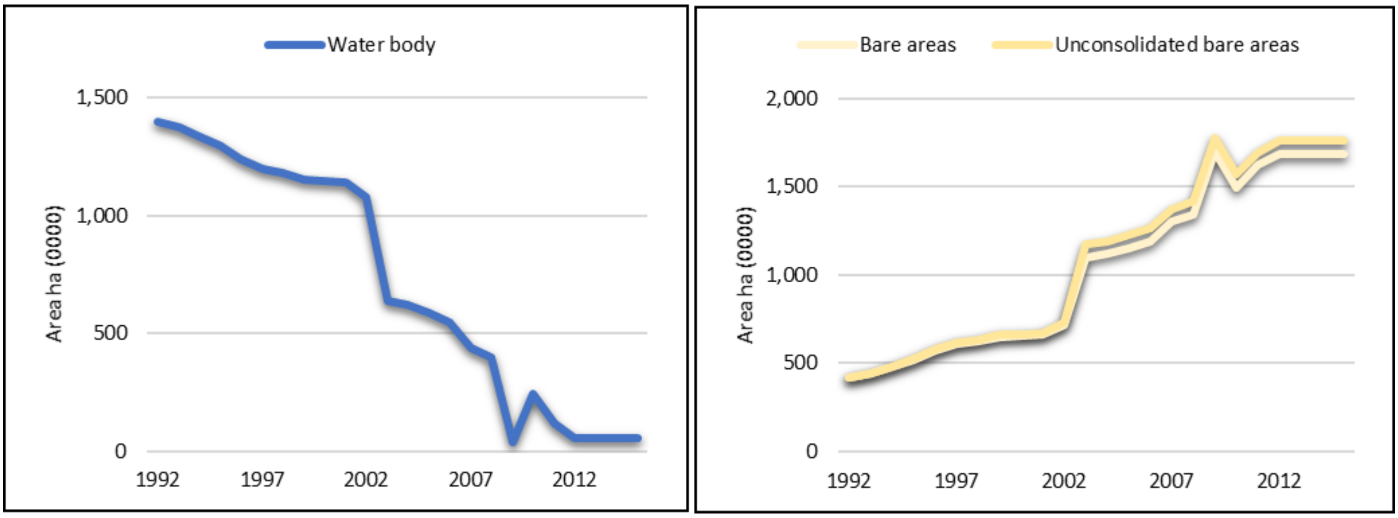


Source: Map constructed by authors.

The drying of the Aral Sea and forming of the Aralkum Desert has a direct impact on the ecosystem balance. The analysis of land cover change within suggested zones in Map 4.1 from 1992–2015 revealed the following:

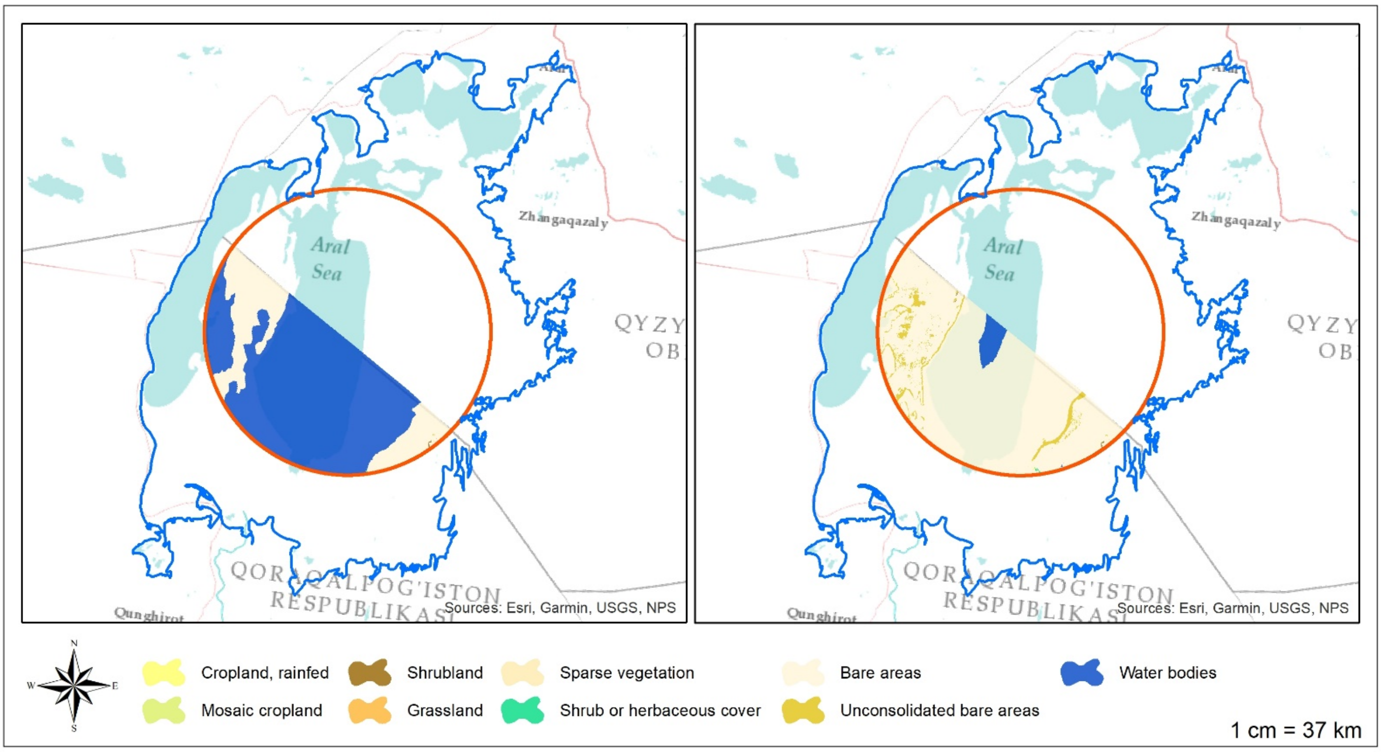
- In the 100 km impact zone, "water body" has decreased dramatically while "bare areas" and "unconsolidated bare areas" increased (Figure 4.1 and Map 4.2).

Figure 4.1 Major Land Cover Changes in the 100 km Impact Zone



Source: Authors' estimates based on ESA Land Cover CCI project team; Defourny, P. (2019): ESA Land Cover Climate Change Initiative (Land_Cover_CCI): Global Land Cover Maps, Version 2.0.7. Centre for Environmental Data Analysis. [*https://catalogue.ceda.ac.uk/uuid/b382ebe6679d44b8b0e68ea4ef4b701c*](https://catalogue.ceda.ac.uk/uuid/b382ebe6679d44b8b0e68ea4ef4b701c).

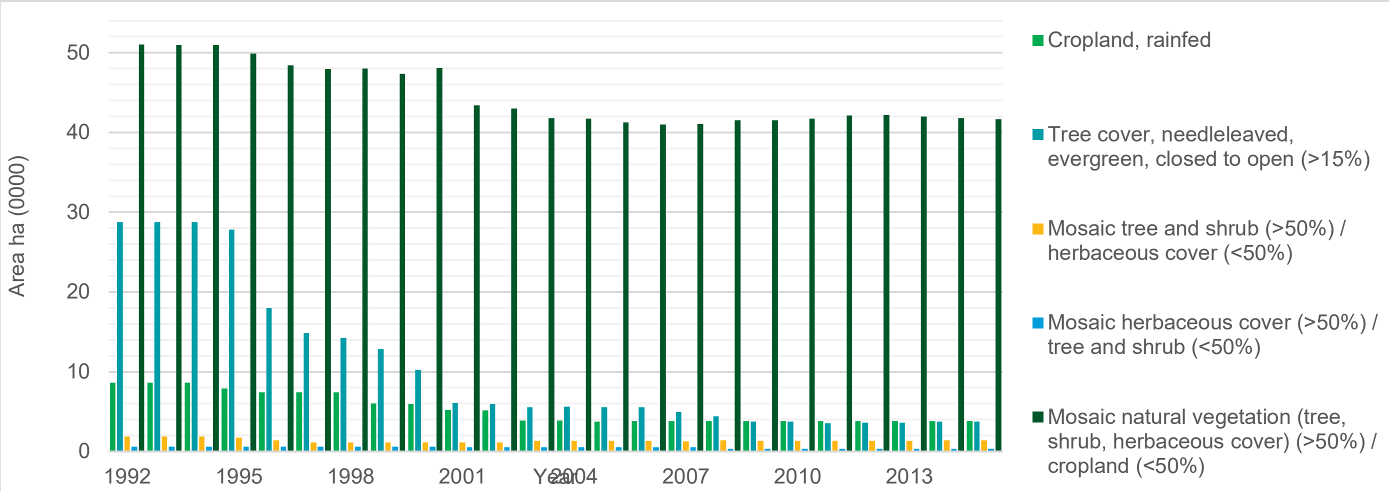
Map 4.2 Land Cover Change Between 1992 (Left) and 2015 (Right) in the 100 km Impact Zone



Source: ESA Land Cover CCI project team; Defourny, P. (2019): ESA Land Cover Climate Change Initiative (Land_Cover_CCI): Global Land Cover Maps, Version 2.0.7. Centre for Environmental Data Analysis. [*https://catalogue.ceda.ac.uk/uuid/b382ebe6679d44b8b0e68ea4ef4b701c*](https://catalogue.ceda.ac.uk/uuid/b382ebe6679d44b8b0e68ea4ef4b701c).

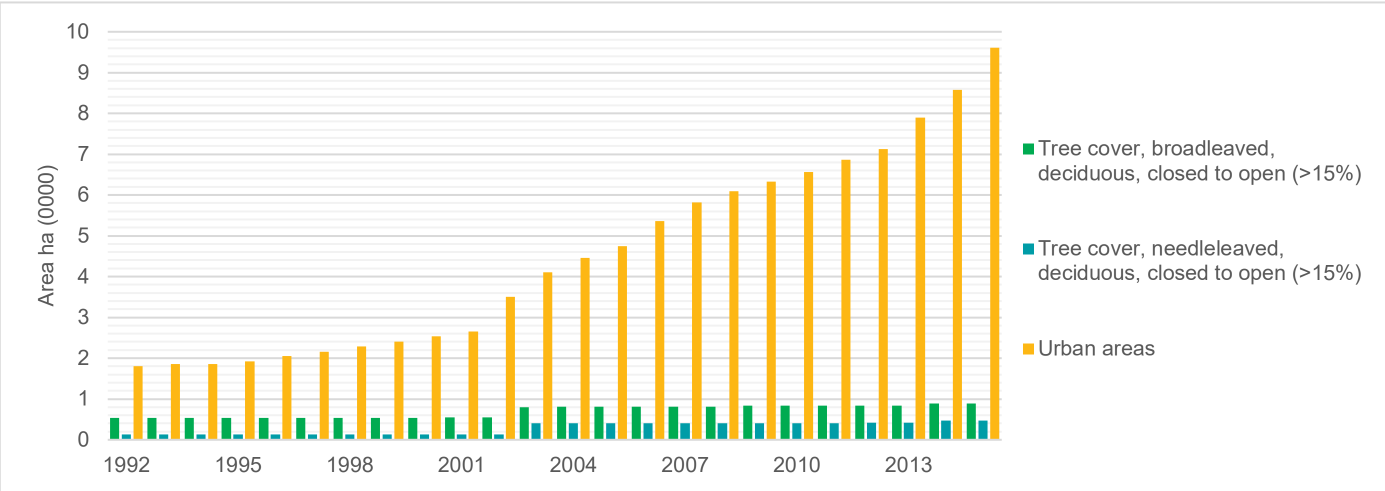
- The area between 100–300 km indicates several changes; for example, areas classified as "cropland" and "tree cover, needle-leaved, evergreen, closed to open (>15%)" declined over time while "urban areas" and "tree cover, broadleaved, deciduous, closed to open (>15%)" increased (Figure 4.2 and Figure 4.3). Also, "water bodies" decreased, and "bare areas" increased similarly to the first impact zone. The spatial representation of the land cover in both 1992 and 2015 is shown in Map 4.3.

Figure 4.2 Land Cover Decline in the 100–300 km Impact Zone



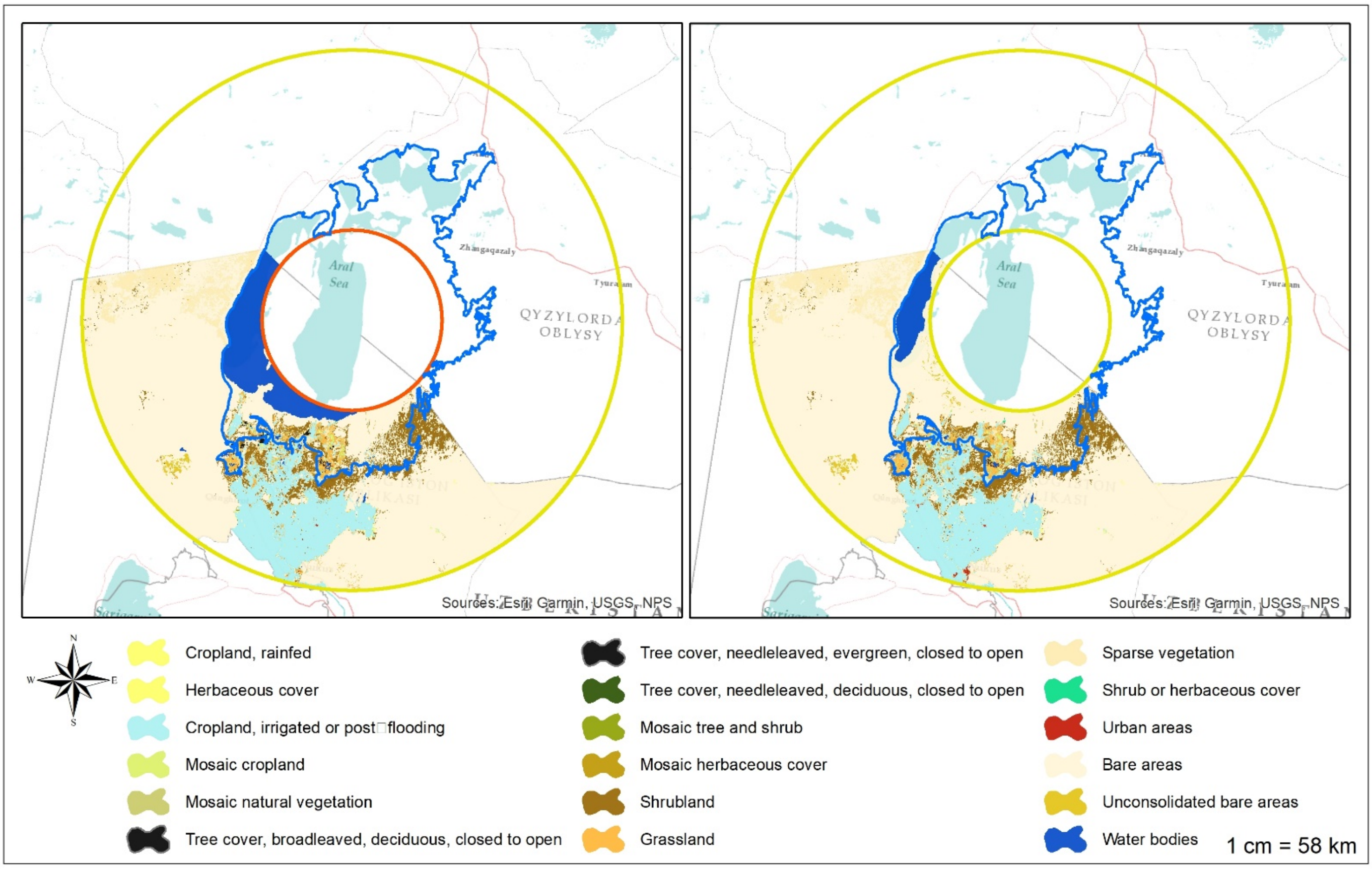
Source: Authors' estimates based on ESA Land Cover CCI project team; Defourny, P. (2019): ESA Land Cover Climate Change Initiative (Land_Cover_CCI): Global Land Cover Maps, Version 2.0.7. Centre for Environmental Data Analysis. https://catalogue.ceda.ac.uk/uuid/b382ebe6679d44b8b0e68ea4ef4b701c.

Figure 4.3 Land Cover Increase in the 100–300 km Impact Zone



Source: Authors' estimates based on ESA Land Cover CCI project team; Defourny, P. (2019): ESA Land Cover Climate Change Initiative (Land_Cover_CCI): Global Land Cover Maps, Version 2.0.7. Centre for Environmental Data Analysis. https://catalogue.ceda.ac.uk/uuid/b382ebe6679d44b8b0e68ea4ef4b701c.

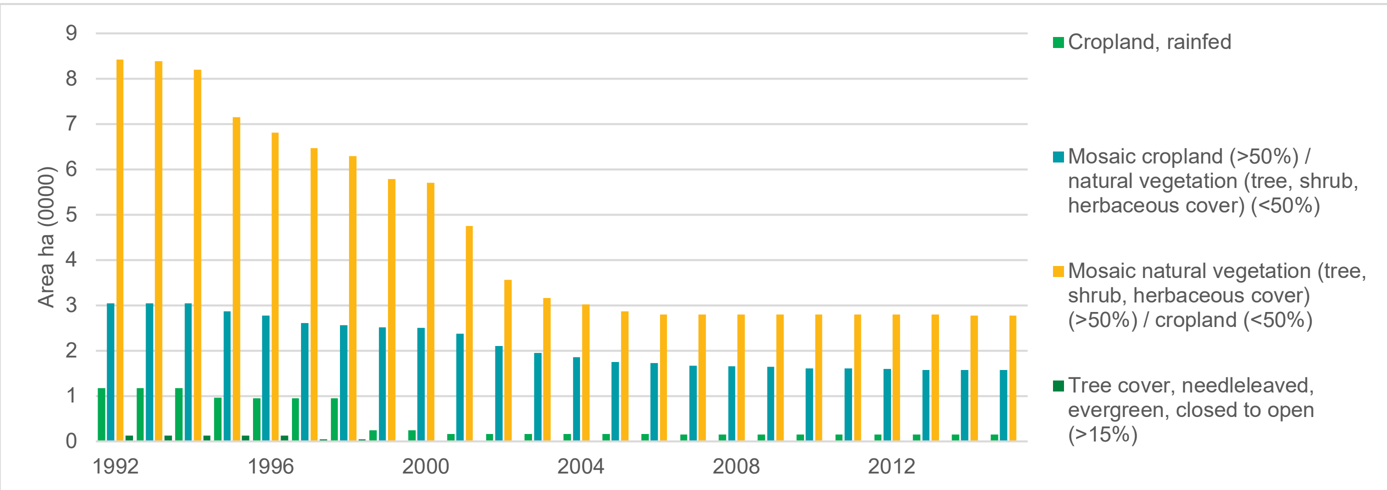
Map 4.3 Land Cover Change Between 1992 (Left) and 2015 (Right) in the 100–300 km Impact Zone



Source: ESA Land Cover CCI project team; Defourny, P. (2019): ESA Land Cover Climate Change Initiative (Land_Cover_CCI): Global Land Cover Maps, Version 2.0.7. Centre for Environmental Data Analysis. https://catalogue.ceda.ac.uk/uuid/b382ebe6679d44b8b0e68ea4ef4b701c.

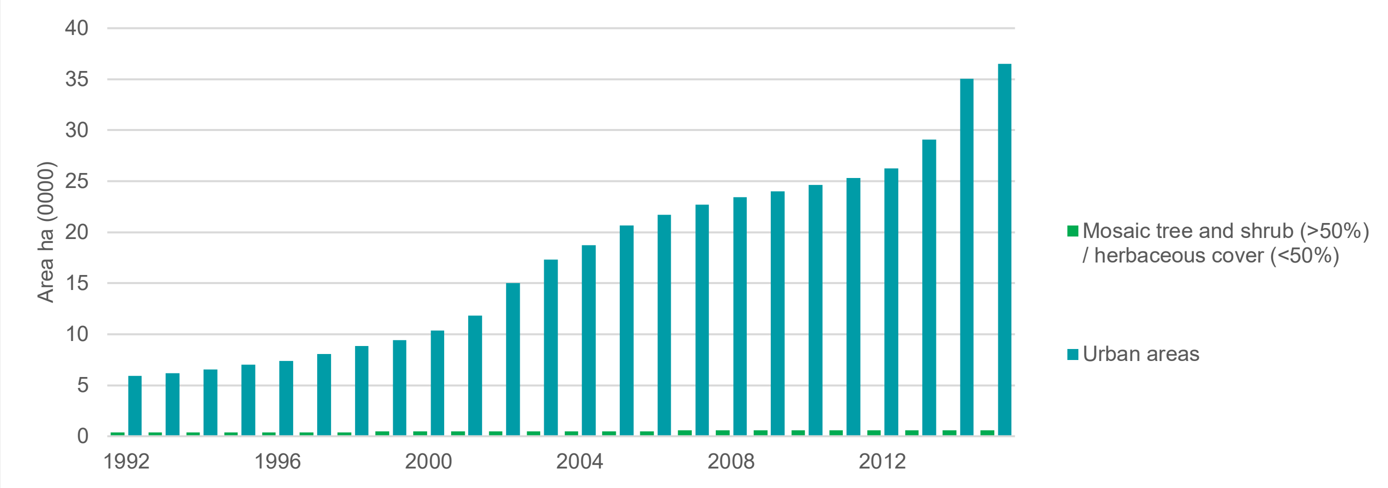
- For areas located in the 300–500 km impact zone, "cropland" declined dramatically together with "mosaic cropland (>50%)/natural vegetation (tree, shrub, herbaceous cover) (<50%)" and "mosaic natural vegetation (tree, shrub, herbaceous cover) (>50%)/cropland (<50%)" with the absence of "tree cover, needle-leaved, evergreen, closed to open (>15%)" after 1998 (Figure 4.4 and Figure 4.5). The spatial representation of the land cover in this zone is shown Map 4.4Map 4.4.
- Based on the analysis, land cover indicated as "cropland, irrigation or post-flooding" in the 100–300 km and 300–500 km impact zones remained unchanged from 1992–2015.

Figure 4.4 Land Cover Decline in the 300–500 km Impact Zone



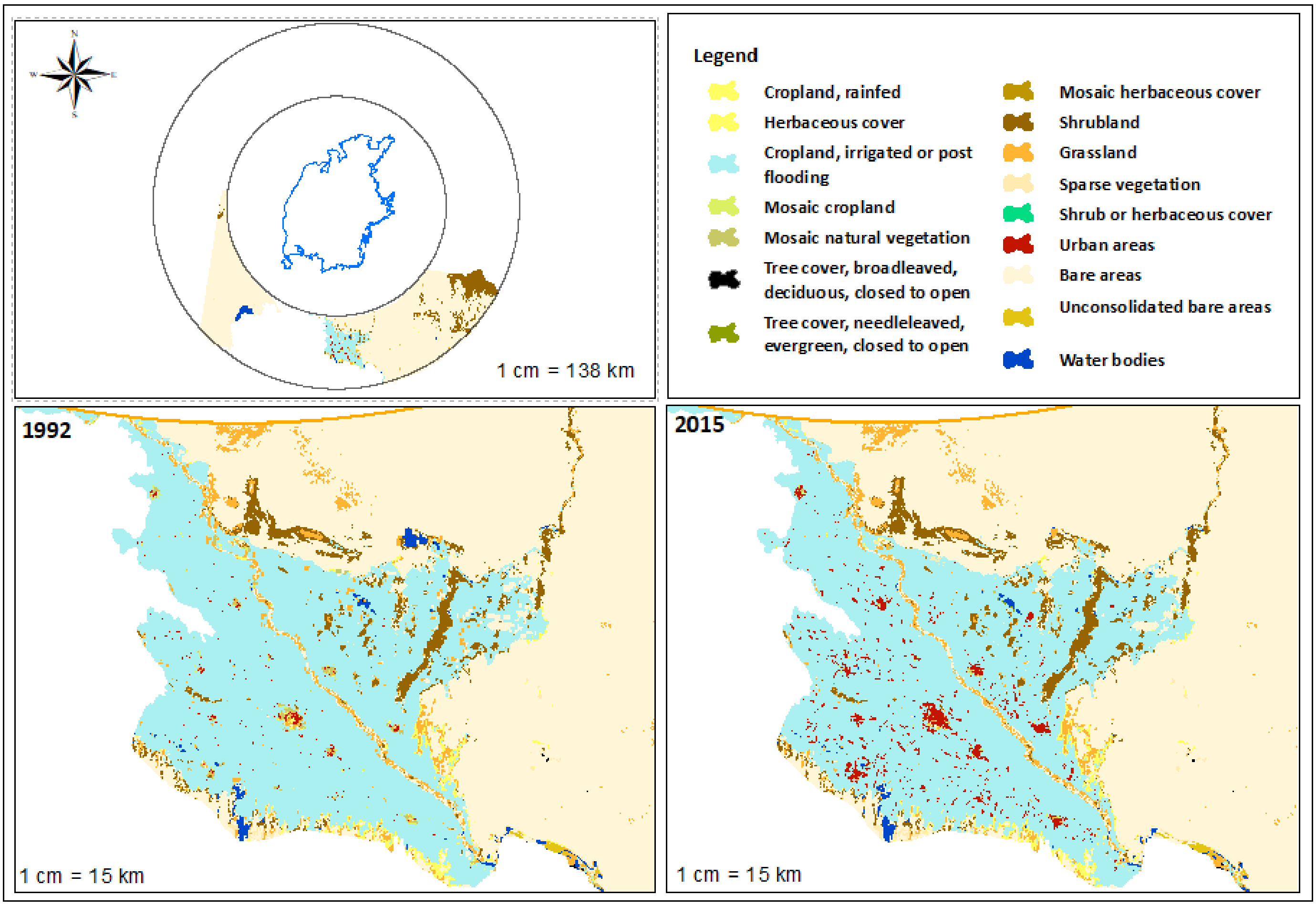
Source: Authors' estimates based on ESA Land Cover CCI project team; Defourny, P. (2019): ESA Land Cover Climate Change Initiative (Land_Cover_CCI): Global Land Cover Maps, Version 2.0.7. Centre for Environmental Data Analysis. https://catalogue.ceda.ac.uk/uuid/b382ebe6679d44b8b0e68ea4ef4b701c.

Figure 4.5 Land Cover Increase in the 300–500 km Impact Zone



Source: Authors' estimates based on ESA Land Cover CCI project team; Defourny, P. (2019): ESA Land Cover Climate Change Initiative (Land_Cover_CCI): Global Land Cover Maps, Version 2.0.7. Centre for Environmental Data Analysis. [*https://catalogue.ceda.ac.uk/uuid/b382ebe6679d44b8b0e68ea4ef4b701c*](https://catalogue.ceda.ac.uk/uuid/b382ebe6679d44b8b0e68ea4ef4b701c)*.*

Map 4.4 Land Cover Change Between 1992 (Left) and 2015 (Right) in 300–500 km Impact Zone



Source: ESA Land Cover CCI project team; Defourny, P. (2019): ESA Land Cover Climate Change Initiative (Land_Cover_CCI): Global Land Cover Maps, Version 2.0.7. Centre for Environmental Data Analysis. [*https://catalogue.ceda.ac.uk/uuid/b382ebe6679d44b8b0e68ea4ef4b701c*](https://catalogue.ceda.ac.uk/uuid/b382ebe6679d44b8b0e68ea4ef4b701c)*.*

4.2. Assessment of Ecosystem Services

4.2.1. On-Site Ecosystem Services

4.2.1.1 Carbon Stock and Biomass Estimation

Above-ground biomass for different scenarios was estimated highest with tree (+) and shrub (+) options constituting 4.40 t/ha and 2.25 t/ha, respectively. For each scenario, a description and vegetation-specific information was set, including plant breadth, height, quantity (No/ha), breadth bark, and porosity. Due to COVID-19, a visit to the Aralkum was not possible. Therefore, with the help of the Uzbekistan State Committee on Forestry, the developed scenarios were validated. One essential ecological variable for vegetation cover is biomass. Values reported by Thevs et al. (2013) were used to estimate above-ground biomass. The carbon content was estimated using 48% of plants' biomass, as suggested by Buras et al. (2012). The carbon content of litter was neglected based on a Thevs et al. (2013) recommendation of deadwood carbon storage in the saxaul vegetation, as its decay is affected by the arid climate. Above-ground biomass of Bare (+) was five to 10 times lower than Tree (+) and Shrub (+) scenarios. Estimated below-ground biomass in Tree (+) and Shrub (+) scenarios was 5.98 t/ha and 2.88 t/ha, respectively, proportionately five to 10 times higher than Bare (+) scenario. Carbon equivalent of above- and below-ground biomass is presented in Table 4.1.

The soil organic carbon stock in the study area varies around 23–25 t/ha depending on land cover. Estimations were based on the International Soil Reference and Information Centre (ISRIC) datasets and on An et al. (2018). Published local soil sampling data (dry Aral Seabed) were merged with the spatial information provided by ISRIC soil grids datasets, generating homogenized soil carbon pools for each dry Aral Seabed zone. The biomass-related carbon values were estimated based on literature on e.g., monitoring of success of saxaul tree planting undertaken in Uzbekistan and Kazakhstan,[11] and the conversion of dry biomass to carbon using a factor of 0.48. For low vegetation performing scenarios (-), a low percentile from various literature references was applied (25th percentile), while for well performing scenarios (+), the larger percentiles were selected (60th and 80th percentiles for shrub and tree scenarios, respectively). Estimated plant biomass and soil organic carbon values are summarized in Table 4.1. The land-cover map of the Aralkum (Map 4.5) demonstrates a large area of bare and sparsely vegetated cover that with Tree (+) and Shrub (+) scenarios can accumulate organic carbon. Organic carbon stored in the soil can contribute the most to the ecosystem services of the Aralkum.

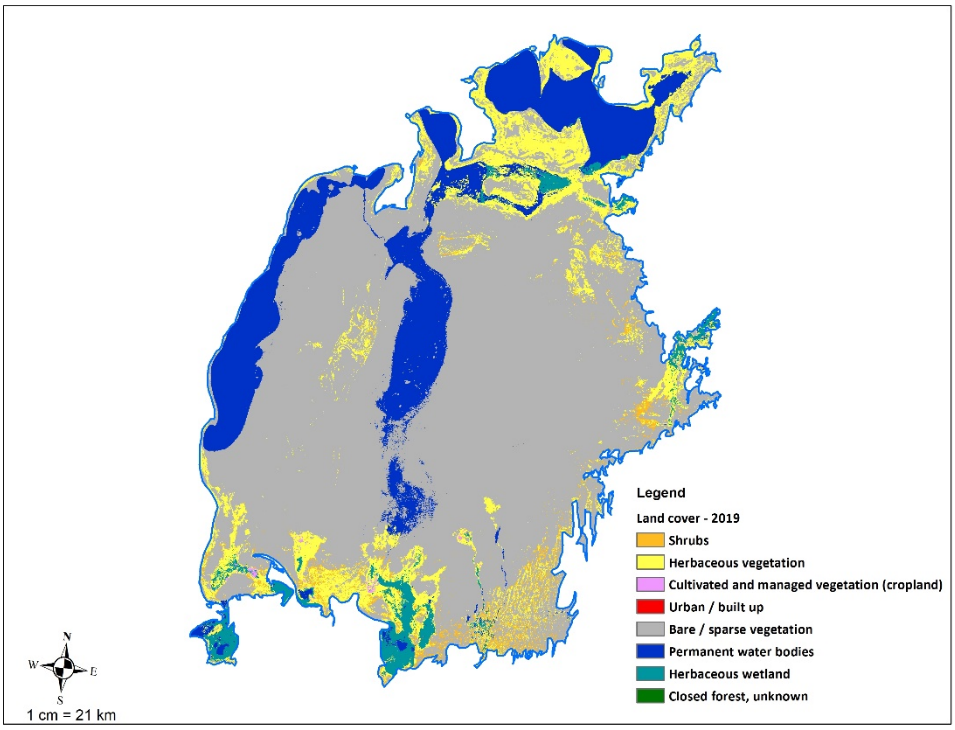
Table 4.1: Biomass and Carbon Stock for Rehabilitation Scenarios

		Biomass (t/ha)		Carbon Stock (t/ha)		
Code	**Scenario**	**Above Ground**	**Below Ground**	**Above Ground**	**Below Ground**	**Soil Carbon**
S1.1	Bare (-)	0.00	0.00	0.00	0.00	23.26
S1.2	Bare (+)	0.40	0.54	0.19	0.26	23.26
S2.1	Shrub (-)	1.50	2.00	0.72	0.96	23.26
S2.2	Shrub (+)	2.25	2.88	1.08	1.38	24.69
S3.1	Tree (-)	2.00	2.80	0.96	1.34	23.26
S3.2	Tree (+)	4.40	5.98	2.11	2.87	25.41

Source: Authors compilation.

[11] A simple tree biomass growth model and a proper soil/sand transport model were used to estimate the annual growth of forest and forage biomass and depletion of soil. The amount of biomass at a given time using a simple tree growth model of the form Y=Y0*(1+r)t where the annual growth rate (r) was estimated from the average full size of a saxaul tree after 20 years. Then, in each of the 20 years, certain percentages of harvestable biomass which is proportional to the growth level of the tree is assumed and the value calculated accordingly.

Map 4.5 Land Cover of the Desiccating Aral Seabed Area in 2019

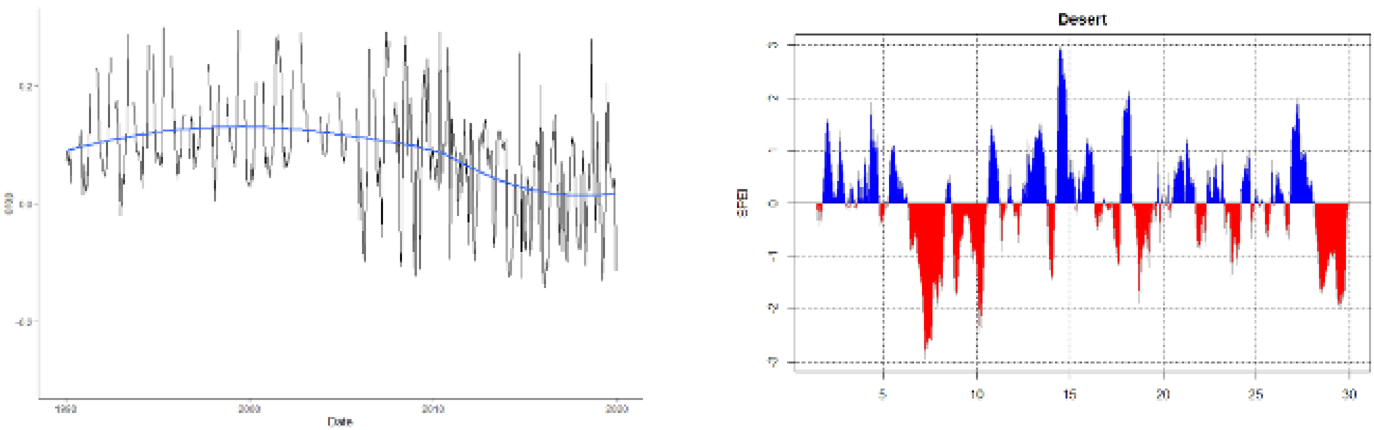


Source: ESA Land Cover CCI project team; Defourny, P. (2019): ESA Land Cover Climate Change Initiative (Land_Cover_CCI): Global Land Cover Maps, Version 2.0.7. Centre for Environmental Data Analysis. [*https://catalogue.ceda.ac.uk/uuid/b382ebe6679d44b8b0e68ea4ef4b701c*](https://catalogue.ceda.ac.uk/uuid/b382ebe6679d44b8b0e68ea4ef4b701c).

4.2.2. Off-Site Ecosystem Services, Vegetation Cover Change

Negative trends and changes in crop vegetation greenness/health occurred after early 2000. Figure 4.6 shows remote sensing-based vegetation trend analysis (NDVI) and its relation/anomalies to drought index, e.g., using Standardized Precipitation Evapotranspiration Index (SPEI). The SPEI compares anomalous dry and wet conditions with the long-term average conditions and has a negative value during droughts (red color in Figure 4.6). However, the SPEI anomalies do not allow conclusions on drought relation.

Figure 4.6 NDVI Trend Over Time (1990–2020) in Off-Site Irrigated Agriculture Areas (Left) and the SPEI Anomalies (Right)

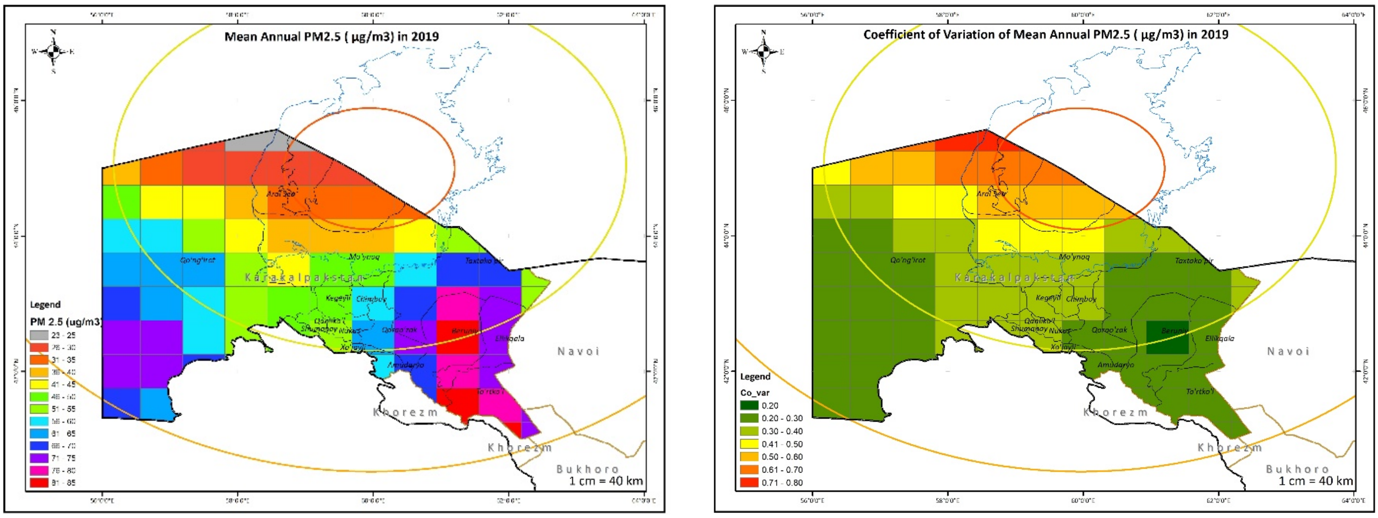


Source: Authors' estimates.

4.2.3. $PM_{2.5}$ Concentration and Impact on Health

As the Aralkum is not the single source of Ambient Air Pollution (AAP) in the region, the share of $PM_{2.5}$ concentration is estimated. The $PM_{2.5}$ data for the 2019 overlaying district and populated areas is presented in Map 4.6. While average dust concentration seems generally larger towards the south (e.g., desert areas towards Turkmenistan), the variance (coefficient of variance) indicates a highly fluctuating dust pattern closer to the Aralkum. The considerable temporal variance might indicate an event-based dust occurrence and therefore identify the dry Aral Seabed and erosive wind events as the source and cause of high dust concentrations around the Aralkum. The weighted average was used to estimate $PM_{2.5}$ concentration for each district. Additional details are provided in Annexes B and C. Determining the shared contribution of the Aralkum into district AAP is based on erosion and dispersion modeling. Assuming areas closer to the source have larger shares of AAP, Table 4.2 provides estimates of the share of the Aralkum in $PM_{2.5}$ data for each district. The impact of SDS originating from the Aralkum is low in Amudaryo, Beruniy, Turtkul, and Elikkala, likely because of the distance from the source. Impact on Moynaq district is the highest as it is located closest to the Aralkum.

Map 4.6 Spatial Distribution of Annual Average (Left) and Coefficient of Variation (Right) $PM_{2.5}$ in Karakalpakstan in 2019



Source: Map constructed by authors.

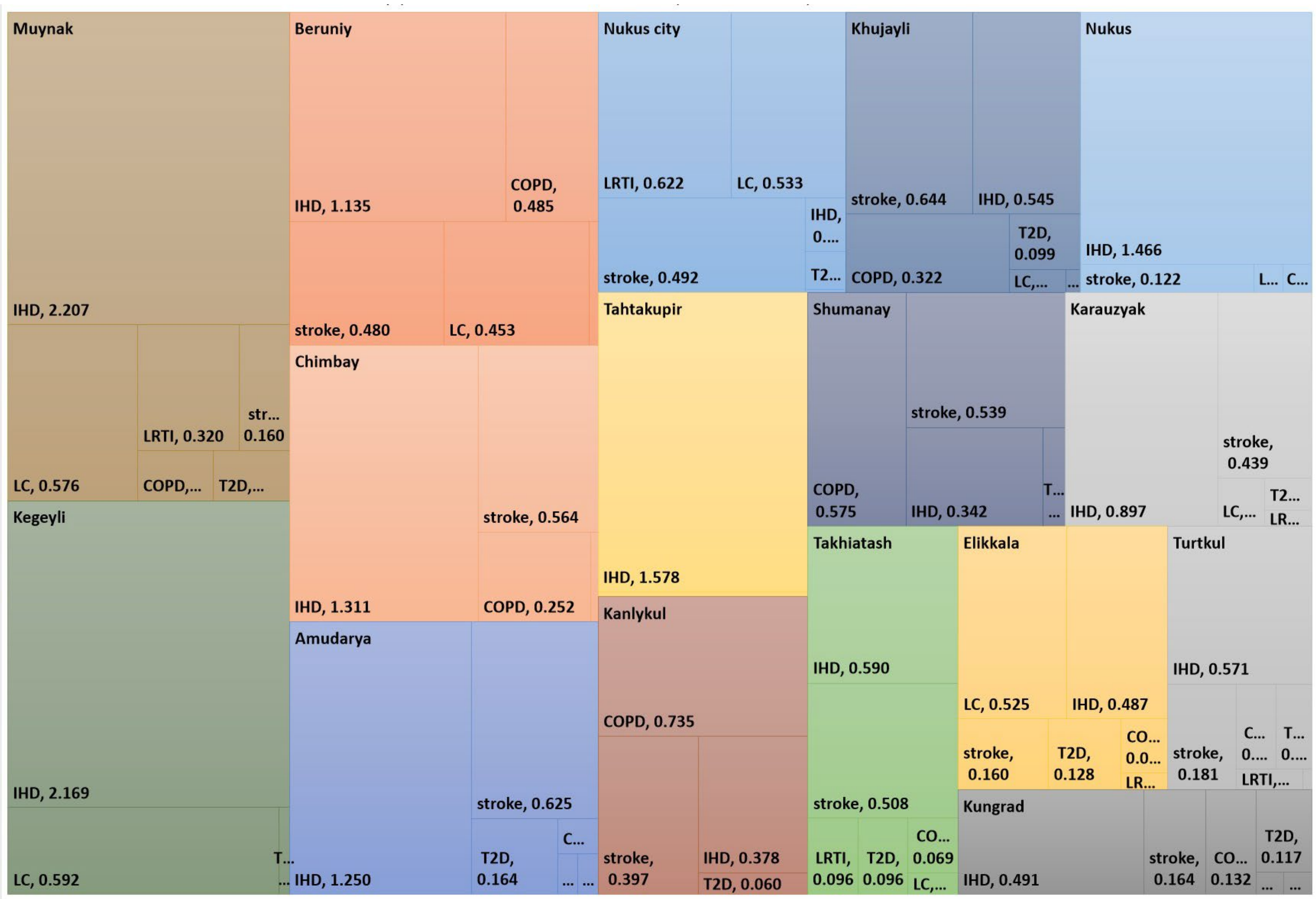
Table 4.2: Annual Average Concentration of $PM_{2.5}$ in 2019 by Districts and SDS Impact Level

No.	District Name	Distance from Aralkum, km	$PM_{2.5}$ ($\mu g/m^3$)	Estimated Share of $PM_{2.5}$ from the Aralkum ($\mu g/m^3$)			
				Lower bound	Average	Upper bound	Impact
1	Moynaq	100-200	41.27	35.08	37.76	40.44	High
2	Tahtakupir	200-300	65.58	8.77	9.44	10.11	Medium
3	Khujayli	200-300	59.97	8.77	9.44	10.11	Medium
4	Chimbay	200-300	53.93	8.77	9.44	10.11	Medium
5	Shumanay	200-300	50.77	8.77	9.44	10.11	Medium
6	Karauzyak	200-300	63.01	8.77	9.44	10.11	Medium
7	Kegeyli	200-300	51.56	8.77	9.44	10.11	Medium
8	Kungrad	200-300	54.34	8.77	9.44	10.11	Medium
9	Kanlykul	200-300	51.28	8.77	9.44	10.11	Medium
10	Nukus	200-300	56.81	8.77	9.44	10.11	Medium
11	Takhiatash	200-300	59.97	8.77	9.44	10.11	Medium
12	Nukus city	200-300	55.28	8.77	9.44	10.11	Medium
13	Amudaryo	300-500	63.77	1.64	1.77	1.90	Low
14	Beruniy	300-500	78.18	1.64	1.77	1.90	Low
15	Turtkul	300-500	79.18	1.64	1.77	1.90	Low
16	Elikkala	300-500	73.48	1.64	1.77	1.90	Low

Source: Authors' estimates.

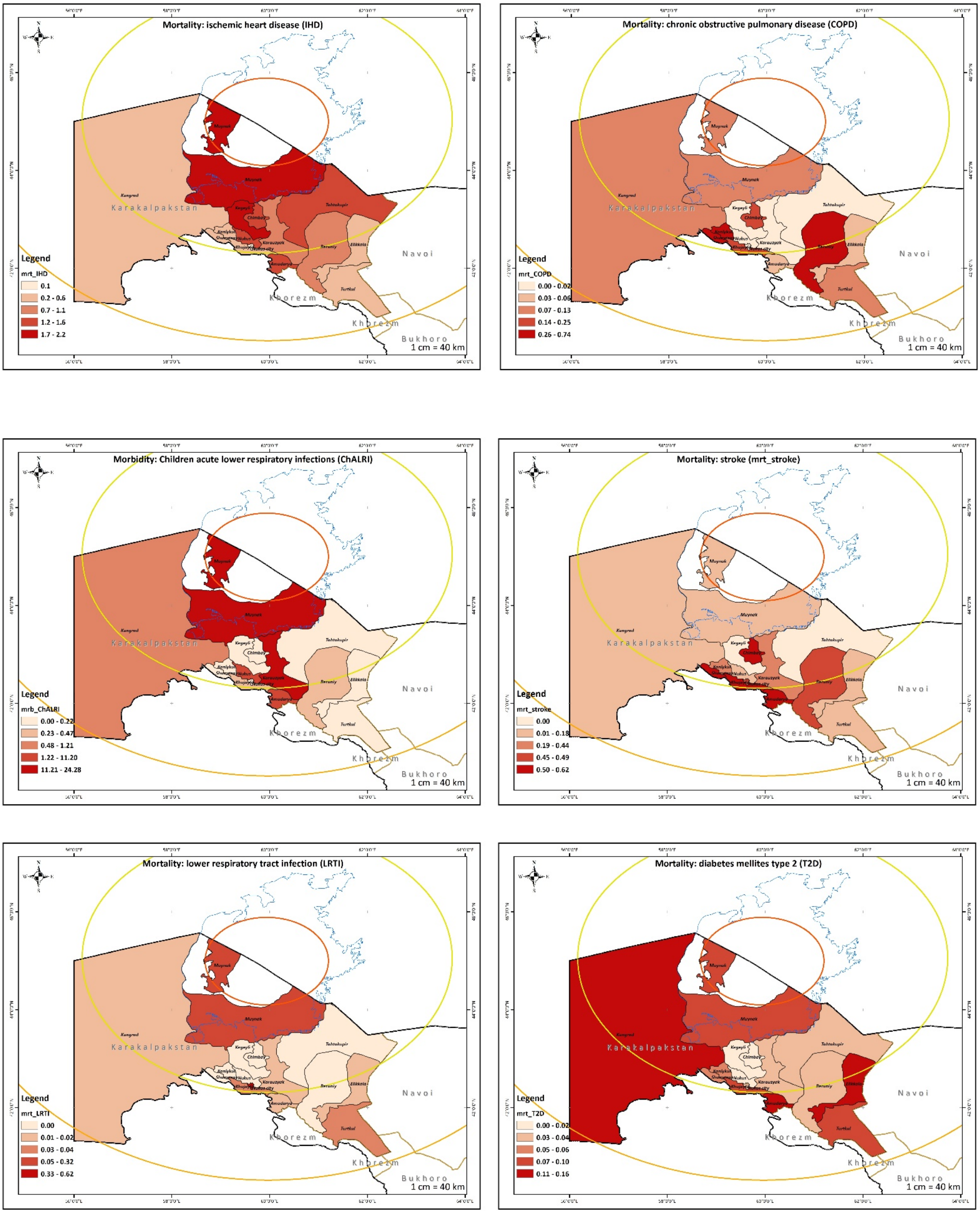
Moynaq and Kegeyli districts, located closest to the Aralkum SDS source, have the highest morbidity as compared to other districts. The following figures provide a summary of health-related data obtained and estimated from local sources. Total number of disease cases was converted to represent district incidence per thousand (Figure 4.7 and Map 4.7) as the population in the districts varies, with more densely populated areas located to the south of Karakalpakstan. (Map 4.8).

Figure 4.7 Mortality (per Thousand) in 2019 by District for Air Pollution-Related Diseases



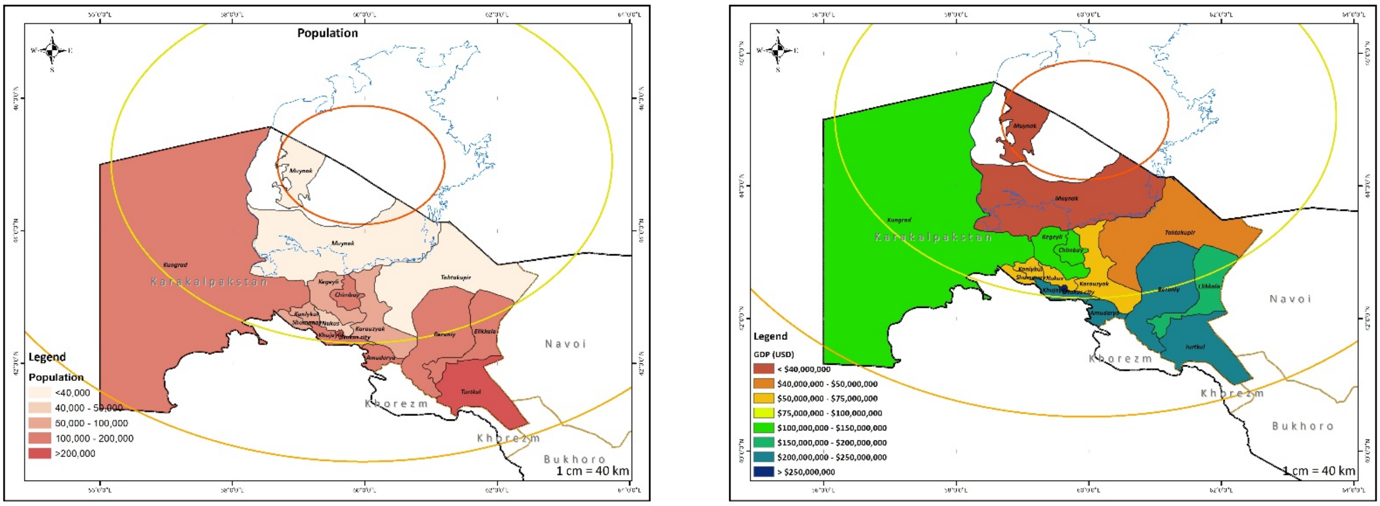
Source: Authors' representation based on the Karakalpakstan Ministry of Health data obtained with support of the Uzbekistan State Committee on Forestry.
Note: Ischemic Heart Disease (IHD), Stroke, Lung Cancer (LC), Chronic Obstructive Pulmonary Disease (COPD), Lower Respiratory Illness (LRI), Diabetes Mellitus Type 2 (T2D).

Map 4.7 Spatial Distribution of Air Pollution-Related Diseases in Karakalpakstan (2019), Estimated per Thousand



Source: Map constructed by authors based on the Karakalpakstan Ministry of Health data obtained with support of the Uzbekistan State Committee on Forestry.

Map 4.8 Spatial Distribution of Population and District Level GDP in 2019 in Karakalpakstan

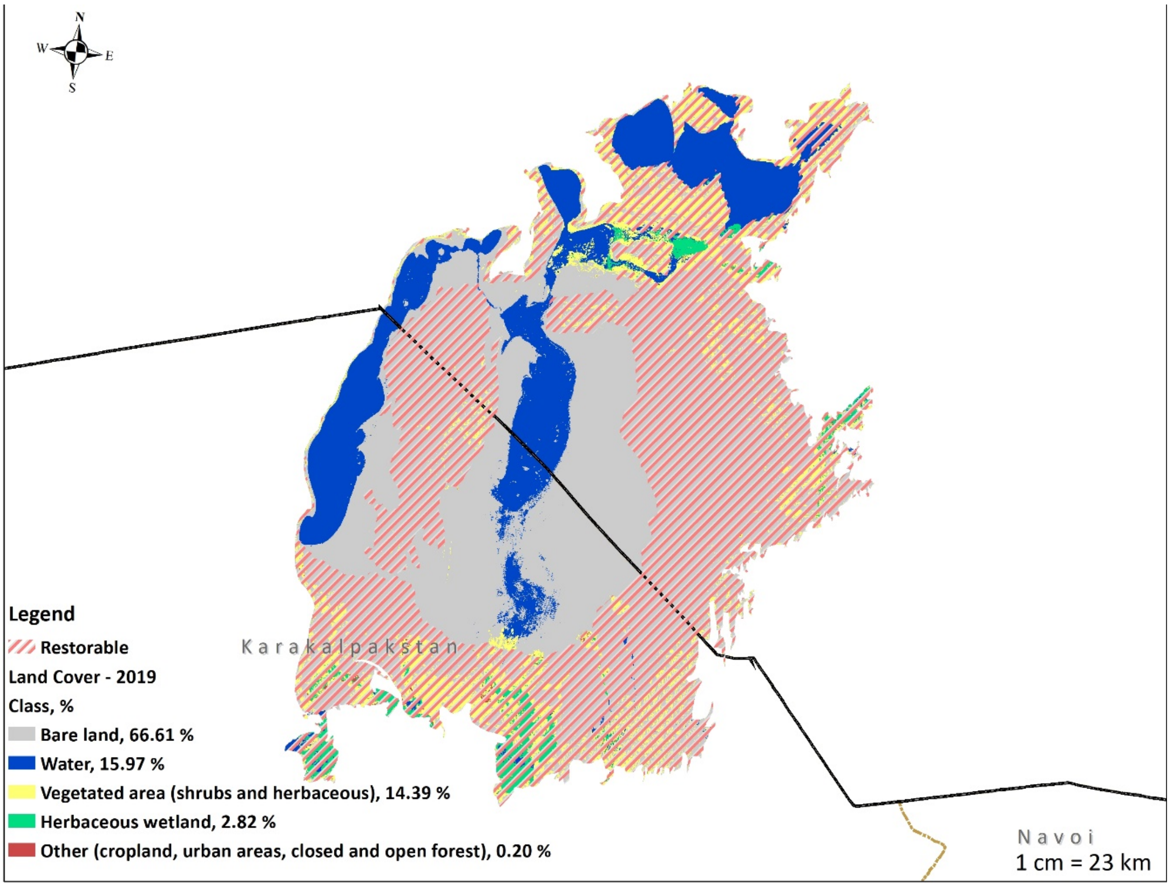


Source: Map constructed by authors based on data from Uzbekistan Statistics Committee (www.stat.uz).

4.3. Costs of SDS Due to Inaction

Desiccation of the Aral Sea has led to a substantial area of bare land subject to significant wind erosion. However, as of 2019, not all the exposed seabed surface is restorable due to either presence of water or shallow groundwater. Map 4.9 depicts the area that is suitable for rehabilitation in the Aral Seabed (see red striped area). While about 2.25 million ha of the Aralkum are located in Uzbekistan, about 58% of this area is restorable (Table 4.3).

Map 4.9 Distribution of Vegetated and Restorable Area of the Aral Seabed



Source: ESA Land Cover CCI project team; Defourny, P. (2019): ESA Land Cover Climate Change Initiative (Land_Cover_CCI): Global Land Cover Maps, Version 2.0.7. Centre for Environmental Data Analysis. https://catalogue.ceda.ac.uk/uuid/b382ebe6679d44b8b0e68ea4ef4b701c.

Table 4.3: Agroecological Classification of the Aralkum

Geographic Region	Restorable Area, ha	Non-restorable Area, ha	Total Area, ha
Total Area of Dried Aral Seabed	3,060,700	1,606,200	4,666,900
Area Located in Uzbekistan	1,322,100	926,400	2,248,500

Source: Authors' estimates based on data from ESA Land Cover CCI project team; Defourny, P. (2019): ESA Land Cover Climate Change Initiative (Land_Cover_CCI): Global Land Cover Maps, Version 2.0.7. Centre for Environmental Data Analysis. https://catalogue.ceda.ac.uk/uuid/b382ebe6679d44b8b0e68ea4ef4b701c.

Considering a planning period of 20 years, inaction can cause Karakalpakstan to lose on-site benefits valued at $652 million. As there is a significant global debate on the appropriate carbon values as well as uncertainty on how carbon values are realized at the local level, a relatively conservative CO_2 price of $10/tonne is used and converted to the carbon price following the World Bank report "*State and Trends of Carbon Pricing 2019*." Simulation results show that, over 20 years, a total of 2.1 million tonnes of soil carbon valued at $207 million has been removed due to SDS from the restorable part of the Aralkum in Uzbekistan. Also, a total of 2.0 and 2.7 million tonnes of carbon (with values of $108 million and $146 million, respectively) that could have been sequestered in the vegetation above and below the ground, respectively, is lost due to SDS. In addition, if the best course of action is taken, rehabilitated landscapes could provide forage and wood.[12] Therefore, the values of forage and wood-related benefits that were forgone were estimated at $111 million and $80 million, respectively. Inaction can cause Karakalpakstan to lose and forgo on-site benefits with an average of $32.6 million/year, equivalent to 1.54% of Karakalpakstan's GDP (Annex Table D.1, Annex Table D.2, and Annex Table D.3).

SDS generated from the dried Aral Seabed lead to off-site effects due to wind erosion exposure, including health impacts and crop production losses, valued on average at $11.6 million/year. The Aralkum is believed to be one of the main sources of SDS in Karakalpakstan. For example, in Moynaq, which is the closest district (100–200 km from the center of the Aral Seabed), between 86–98% of total AAP is attributed to SDS from the Aralkum (Groll et al., 2019). Results of the dispersion model show that the contribution of the Aralkum to total AAP decreases exponentially with distance. Based on these results, the annual values of production losses for all major crops grown in Karakalpakstan are estimated to be between $5–14 million with an average of about $9.9 million, which is equivalent to 0.45% of Karakalpakstan's GDP (Annex Table E.1). The annual number of statistical lives lost (SLL) attributable to SDS from the Aralkum is estimated to be 13–29 in this sparsely populated area, with an average of approximately 21. The welfare loss of SLL/year is approximately $1.7 million/year, equivalent to 0.08% of Karakalpakstan's GDP (Table 4.4 **.**). Economic costs of SDS-related health impacts from the Aralkum are minor compared to other costs given the relatively low population density of the near Aral Sea region. Therefore, over a period of 20 years, the total loss of off-site benefits is approximately $192 million.

Under existing conditions and assuming a 20-year time horizon, inaction is causing Karakalpakstan to lose potential benefits of $782–986 million. The loss of on-site and off-site ecosystem services, as well as forgone benefits, including timber, firewood, and forage production are estimated at $44.2 million/year— equivalent to 2.1% of Karakalpakstan's GDP.

[12] During the growing period, the saxaul trees, can be pruned annually to enhance vegetative growth. The leafy parts of the harvested branches can be used as forage for animals while the harder parts can be used as fuel wood and construction material. Therefore, these benefits are estimated in addition to the value of sequestered carbon in the above-ground biomass of the fully matured trees.

Table 4.4: SLL Estimates and Monetary Value of Lives Lost in Karakalpakstan Due to SDS from the Aralkum

Item	Value	As % of Karakalpakstan's GDP
Total value of health damages in Karakalpakstan due to Ambient Air Pollution (AAP) regardless of source ($)	7,859,798	0.37%
Total number of deaths due to AAP regardless of source (persons/year)	97	
Total number of deaths regardless of cause (persons/year)	3,270	
Lower bound for total value of health damages due to SDS from the Aralkum ($/year)	1,074,803	0.05%
Upper bound for total value of health damages in Karakalpakstan due to SDS from the Aralkum ($/year)	2,354,896	0.11%
Average total value of health damages due to SDS from the Aralkum ($/year)	**1,714,850**	**0.08%**
Share of SDS from the Aralkum in the total value of health damage due to total $PM_{2.5}$ (%)	21.82%	
Lower bound for the total number of deaths due to SDS from the Aralkum (persons/year)	13.26	
Upper bound for the total number of deaths due to SDS from the Aralkum (persons/year)	29.06	
Average of the total number of deaths due to SDS from the Aralkum (persons)	21.16	
Share of SDS from the Aralkum in the total number of deaths due to total $PM_{2.5}$ (%)	21.82	
Share of AAP in the total number of deaths (%)	2.97	
Share of SDS from the Aralkum in total deaths due to AAP (%)	21.82	
Share of SDS from the Aralkum in total deaths (%)	0.65	

Source: Authors' estimates.

4.4. Benefits of Alternative Intervention Scenarios

Three alternative outcomes—low, average, and high—are developed for each scenario to reflect potential success rates of planting and robustness of results. The literature shows varying levels of success/failure rates of tree planting (restoration) depending on the agro-ecologies where planting was done and the weather conditions of the year under consideration (see Annex Table A.3). The averages for the minimum and maximum reported success rate from the literature are utilized to establish the lower bound and upper bound outcomes. Hence, the following assumed cumulative total success rates are used:

- Lower bound: 49.5% (15.69% for the first planting and 1.57% natural succession, 15.69% for the second replanting with 3.16% natural succession, and 15.69% for the third replanting with 4.78% natural succession).
- Average: 72.3% (25.07% for the first planting and 2.51% natural succession, 25.07% for the second replanting with 5.08% natural succession, and 25.07% for the third replanting with 7.71% natural succession).
- Upper bound: 79.4% (43.3% for the first planting and 4.33% natural succession and 43.3% for the second replanting with 8.85% natural succession with no third replanting but high natural succession rate of 9.23%).

4.4.1. On-Site Benefits

On-site benefits of landscape restoration, including the prevention of ecosystem service losses and regeneration of new ecosystem services, have a range of $146–699 million. Considering a planning period of 20 years, simulation results show that, by intervening with planting of different vegetative covers and distinct levels of success rates (in terms of percentage of total area covered by shrubs and/or trees), the value of ecosystem services prevented from being lost and regenerated can vary widely. Benefits of restoration are estimated as the difference in ecosystem services (annual flows) provided under rehabilitation scenarios and the base case scenario. Shrub-based intervention (Scenario 2) in the Aral Seabed can provide on-site benefits of $146–207 million over a 20-year time horizon (Annex Table D.1 and Annex Table D.3). In turn, the implementation of best-bet practices, including the planting of saxaul trees and grasses, can lead to additional on-site benefits of $488–699 million.

The prevention of soil carbon loss and the regeneration of provisioning services, such as wood, increase the value of restorable land in the Aralkum by a range of $111–529/ha. These figures are lower compared to the estimates in other studies, e.g., $1,588/ha for temperate forests (de Groot et al., 2012) and $1,588/ha (Costanza et al., 2014), or the estimates of unrestored or unforested deserts, which are also relatively high, including $173.84/ha (Kroeger and Manalo, 2007) and $234/ha (Costanza et al., 2014). In comparison, the estimates made in this study can be considered extremely conservative.

4.4.2. Off-Site Benefits

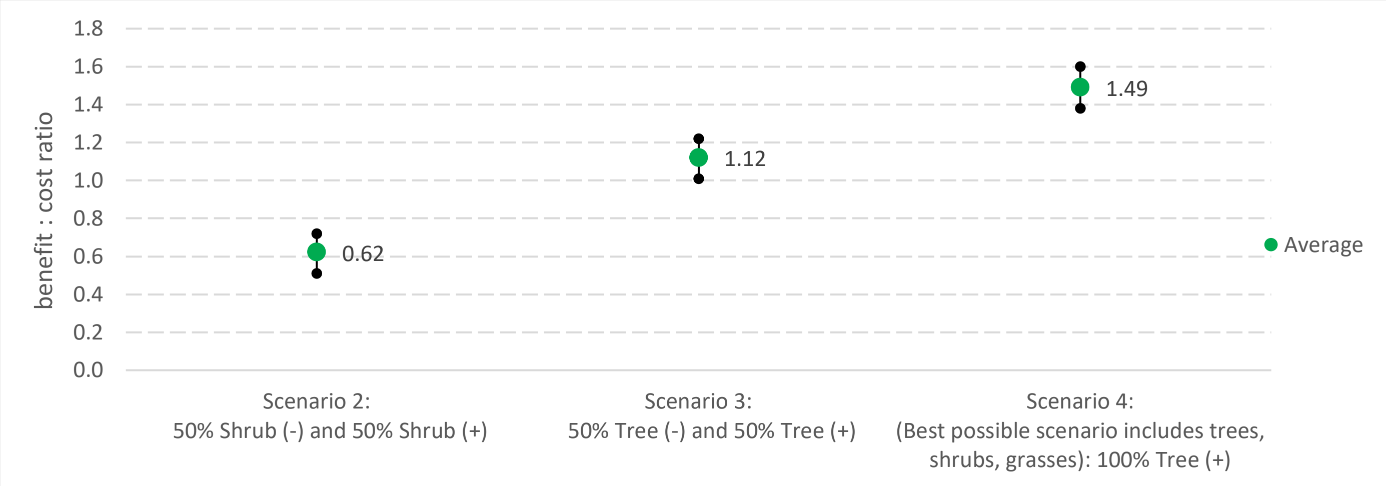
Estimates show that different interventions have varying effects on the magnitude of crop production loss due to SDS from the Aralkum. Estimates of different intervention scenarios on the total production of specific crops and the total monetary values by district are given in Table 4.5. While the interventions under Scenarios 2 and 3 have sizeable effects in the reduction of crop loss, the intervention under Scenario 4 (i.e., planting of 100% saxaul trees, allowing undergrowth of grass) provides the best outcome. The total value of crop production in Karakalpakstan lost due to SDS from the Aralkum under the current scenario is estimated at an average of $9.88 million/year, which is expected to decrease by 56% to $4.36 million/year if the best practices of planting 100% saxaul trees is implemented—saving the country $5.52 million/year.

By implementing different intervention scenarios to reduce SDS from the Aralkum, it is possible to reduce negative health impacts to a range of $0.075–0.242 million (i.e., by 8–96%). The economic value of SLL/year is estimated at approximately $1.7 million, equivalent to 0.08% of Karakalpakstan's GDP. Summaries of lower and upper bound estimates of AAP health impacts caused by SDS from the Aralkum are provided in Annex Table E.2, Annex Table E.3 and Annex Table E.4. Under vegetation-based rehabilitation, the burden on human health decreases due to the decreased share of $PM_{2.5}$ concentration originating from the Aralkum. Under shrub-based intervention, the average benefit of rehabilitation is at $719,000 / year (i.e., 42% reduction of health costs compared to average Scenario 1). Under the best-bet scenario, the negative health impacts related to SDS from the Aralkum can be reduced on average by 58%, leading to an annual benefit of $1 million.

The implementation of different intervention scenarios to restore the Aralkum can generate total annual benefits ranging between $10–44 million. Table 4.6 provides a summary of total annual values of on-site and off-site ecosystem services gained assuming different intervention scenarios. The annual Present Value (PV) based on different interventions per ha of land that is restored in the Aralkum Desert ranges between $7/ha/year (the lower bound estimate of Scenario 2) and $34/ha/year (the upper bound of Scenario 4).

Estimated values of Benefit-to-Cost-Ratio (BCR) of the different interventions (Figure 4.8) range from 0.5 (the lower bound estimate of Scenario 2) to 1.6 (the upper bound of Scenario 4). Considering only the best scenario of 100% planting of saxaul trees, estimates of the BCR range between 1.38 and 1.60 with an average of 1.49. These ratios may appear rather low, given that: 1) estimates were based on extremely conservative assumptions, and 2) several other damages from SDS and benefits from the restoration of the Aralkum are ignored. Therefore, the results represent the lower bound costs of inaction and the lower bound benefits that can be expected from action. The relatively modest estimate of economic return of landscape restoration in the Aral Seabed highlights the need for careful planning and use of appropriate restoration methods to ensure benefits are greater than the cost. Moreover, restoration projects in the Aralkum have the potential to deliver regional and global benefits in addition to the economic return calculated in this study. These benefits contribute to the Nationally Determined Contribution (NDC) targets, Land Degradation Neutrality goals, and the Bonn Challenge, among others.

Figure 4.8 BCR for Different Scenarios Representing Lower Bound, Average and Upper Bound Values



Source: Authors' estimates.

Table 4.5: Impacts of Implementing the Best Course of Action on the Total Value of Production Lost Due to SDS from the Aralkum

		Value of Total Production Loss Due to SDS from the Aralkum ($, million)												The Value of Production Loss that can be Prevented by Implementing the Best Course of Action (Scenario 4)		
		Scenario 1 (Base-Case)			Scenario 2 (50%-50% Shrub (-) & Shrub (+))			Scenario 3 (50%-50% Tree (-) & Tree (+))			Scenario 4 (100% Tree (+))					
		Loss: Lower Bound ($, million)	Loss: Average ($, million)	Loss: Upper Bound ($, million)	Loss: Lower Bound ($, million)	Loss: Average ($, million)	Loss: Upper Bound ($, million)	Loss: Lower Bound ($, million)	Loss: Average ($, million)	Loss: Upper Bound ($, million)	Loss: Lower Bound ($, million)	Loss: Average ($, million)	Loss: Upper Bound ($, million)	Loss: Lower Bound ($, million)	Loss: Average ($, million)	Loss: Upper Bound ($, million)
Nukus City	4.51	0.08	0.15	0.23	0.03	0.07	0.10	0.03	0.07	0.10	0.03	0.06	0.09	0.05	0.10	0.15
Amudaryo	121.83	0.33	0.65	0.98	0.15	0.29	0.44	0.14	0.29	0.43	0.11	0.22	0.33	0.22	0.43	0.65
Beruniy	59.27	0.16	0.32	0.48	0.07	0.14	0.21	0.07	0.14	0.21	0.05	0.11	0.16	0.11	0.21	0.32
Karauzyak	18.08	0.31	0.62	0.93	0.14	0.28	0.41	0.14	0.27	0.41	0.11	0.23	0.34	0.20	0.39	0.59
Kegeyli	22.34	0.38	0.77	1.15	0.17	0.34	0.51	0.17	0.33	0.50	0.14	0.28	0.42	0.24	0.48	0.73
Kungrad	25.72	0.44	0.88	1.32	0.20	0.39	0.59	0.19	0.39	0.58	0.16	0.32	0.49	0.28	0.56	0.84
Kanlykul	16.76	0.29	0.57	0.86	0.13	0.26	0.38	0.13	0.25	0.38	0.11	0.21	0.32	0.18	0.36	0.55
Moynaq	4.26	0.43	0.85	1.28	0.39	0.78	1.17	0.39	0.78	1.16	0.38	0.77	1.15	0.04	0.09	0.13
Nukus	31.31	0.78	0.61	0.44	0.71	0.56	0.40	0.71	0.56	0.40	0.70	0.55	0.40	0.08	0.06	0.04
Takhiatash	9.19	0.16	0.31	0.47	0.07	0.14	0.21	0.07	0.14	0.21	0.06	0.12	0.17	0.10	0.20	0.30
Tahtakupir	16.07	0.28	0.55	0.83	0.12	0.25	0.37	0.12	0.24	0.36	0.10	0.20	0.30	0.17	0.35	0.52
Turtkul	57.58	0.15	0.31	0.46	0.07	0.14	0.21	0.07	0.13	0.20	0.05	0.10	0.16	0.10	0.20	0.31
Khujayli	21.14	0.36	0.72	1.09	0.16	0.32	0.48	0.16	0.32	0.48	0.13	0.27	0.40	0.23	0.46	0.69
Chimbay	45.05	0.77	1.54	2.32	0.34	0.69	1.03	0.34	0.68	1.01	0.28	0.57	0.85	0.49	0.98	1.47
Shumanay	22.49	0.39	0.77	1.16	0.17	0.34	0.52	0.17	0.34	0.51	0.14	0.28	0.42	0.24	0.49	0.73
Elikkala	44.28	0.12	0.24	0.36	0.05	0.11	0.16	0.05	0.10	0.16	0.04	0.08	0.12	0.08	0.16	0.24
Total	**519.88**	**5.42**	**9.88**	**14.35**	**2.98**	**5.09**	**7.19**	**2.94**	**5.01**	**7.09**	**2.61**	**4.36**	**6.11**	**2.81**	**5.53**	**8.24**
% of GDP	*24.61%*	*0.26%*	*0.47%*	*0.68%*	*0.14%*	*0.24%*	*0.34%*	*0.14%*	*0.24%*	*0.34%*	*0.12%*	*0.21%*	*0.29%*	*0.13%*	*0.26%*	*0.39%*

Source: Authors' estimates.

Table 4.6: Average Annual Values of On-Site and Off-Site Ecosystem Services Under Different Rehabilitation Scenarios

Scenarios		Annual Losses[13]						Annual Total Benefits of On-Site and Off-Site Ecosystem Services Compared to the Base Case (Scenario 1)					
		On-Site ($, million)[14]			Off-Site ($, million)[15]								
		Soil Carbon	Above/ Below Ground Biomass	Forage and Firewood	Crop Yields	Health	Total ($, million)	Value Gained from Action ($/year, million)	Avg PV[16] of Action ($/year/ha)	As % of Karakalpakstan's GDP	Annual Cost of Action ($, million)	Avg NPV of Action ($/ year/ ha)	Annual, BCR (assuming a period of 20 years)
Scenario 1 *(Current Scenario):* 90% Bare (-) and 10% Bare (+)	*Min*	10.3	12.7	9.6	5.4	1.1	39.1						
	Avg	10.3	12.7	9.6	9.9	1.7	44.2						
	Max	10.3	12.7	9.6	14.3	2.4	49.3						
Scenario 2: 50% Shrub (-) and 50% Shrub (+)	*Min*	6.9	7.5	7.5	3.0	0.7	25.6	13.5	10.21	0.64%	26.2	-9.63	0.51
	Avg	6.9	7.5	7.5	5.1	1.0	28.0	16.2	10.97	0.77%	26.2	-8.87	0.62
	Max	6.9	7.5	7.5	7.2	1.3	30.3	18.9	14.33	0.90%	26.2	-5.51	0.72
Scenario 3: 50% Tree (-) and 50% Tree (+)	*Min*	5.1	3.4	0.4	2.9	0.7	12.6	26.5	20.05	1.25%	26.2	0.21	1.01
	Avg	5.1	3.4	0.4	5.0	1.0	14.9	29.3	20.84	1.39%	26.2	1	1.12
	Max	5.1	3.4	0.4	7.1	1.3	17.3	32.0	24.23	1.52%	26.2	4.38	1.22
Scenario 4: (best possible scenario): 100% Tree (+)	*Min*			-	2.6	0.2	2.8	36.3	27.47	1.72%	26.2	7.63	1.38
	Avg			-	4.4	0.7	5.1	39.1	28.29	1.85%	26.2	8.45	1.49
	Max			-	6.1	1.3	7.4	41.9	31.71	1.98%	26.2	11.86	1.6

Source: Authors' estimates.
Note: In 2019, the GDP of Karakalpakstan was $2,112,874,907. The total cost of planting saxaul trees or other shrubs on the Uzbekistan side of the restorable part of the Aralkum (assuming arial planting of 85% of the area and manual planting for the remaining 15%) is estimated at $462,082,634.48.

[13] Considering a 20-year planning period, the total values of soil carbon, above and below ground biomass, crop yields and human lives lost are estimated at $652 million (see Annex Table D.2). The annual impacts reported in Table 4.6 are generated by dividing total impacts reported in Annex Table D.2 by the number of years in the planning period (i.e., by 20).
[14] For quantities and values of total on-site impacts of SDS from the Aralkum see Annex D.
[15] For quantities and values of total off-site impacts of SDS from the Aralkum see Annex E.
[16] A discount rate of 9% is used based on IndexMundi. 2020. Uzbekistan Central Bank discount rate. Available at: https://www.indexmundi.com/uzbekistan/central_bank_discount_rate.html (accessed on April 20, 2021).

4.5. Scenarios with the Highest Net Return

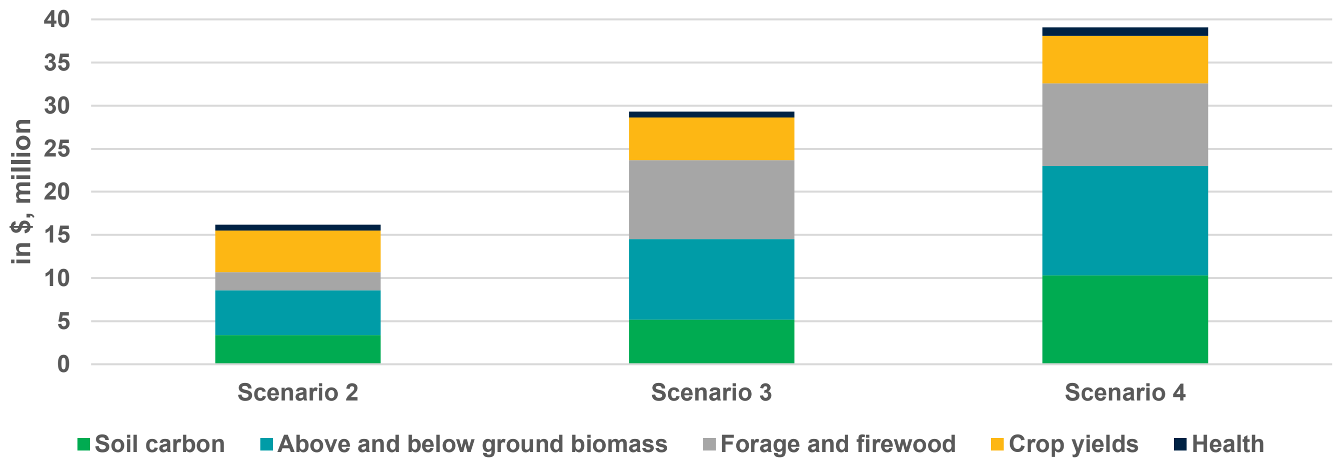
Scenario 4, comprising planting of saxaul trees and undergrowth of grass on 100% of the area provides the highest net return (Figure 4.9). Benefits from vegetative rehabilitation increase per scenario compared to the base case representing the actual Aral Seabed characterized by dried-up areas with no vegetation cover. While annual incremental benefits reach $16.2 million under shrubs-based intervention (Scenario 2), approximately $39.1 million/year can be gained under the best-bet practices of saxaul trees and undergrowth of grass compared to the base case (Scenario 1). The best scenario of 100% planting of saxaul tree leads to an estimated BCR range between 1.38 and 1.60 with an average of 1.49 (Figure 4.10).

Approximately $23 million, or 59% of total benefits, represent soil carbon and biomass above and below the ground (Figure 4.9). Simulation of SDS events with rehabilitation scenarios indicate a clear effect that the vegetation has in minimizing soil carbon erosion by wind. In addition, planting increases the sequestered carbon in above and below ground biomass. During the growing period, the saxaul trees can be pruned annually to enhance vegetative growth. The leafy parts of the pruned tree branches can be used as forage for animals while the harder parts can be used as firewood and construction material. These annual benefits of $9.6 million under best-bet practice are estimated in addition to the value of sequestered carbon in the above ground biomass of the fully matured trees.

The best-bet practice (Scenario 4) reduces the number of SLL as well as crop production losses attributable to SDS from the dry Aral Seabed significantly (Figure 4.9). The value of mortality reduction due to rehabilitation measures is equivalent to $1 million, representing a 58% reduction from the base case scenario—equivalent to 0.05% of Karakalpakstan's GDP (Table 4.7). The planting of saxaul trees and grass undergrowth would prevent crop production losses in Karakalpakstan of approximately $5.5 million—equivalent to 0.26% of Karakalpakstan's GDP. (Table 4.5).

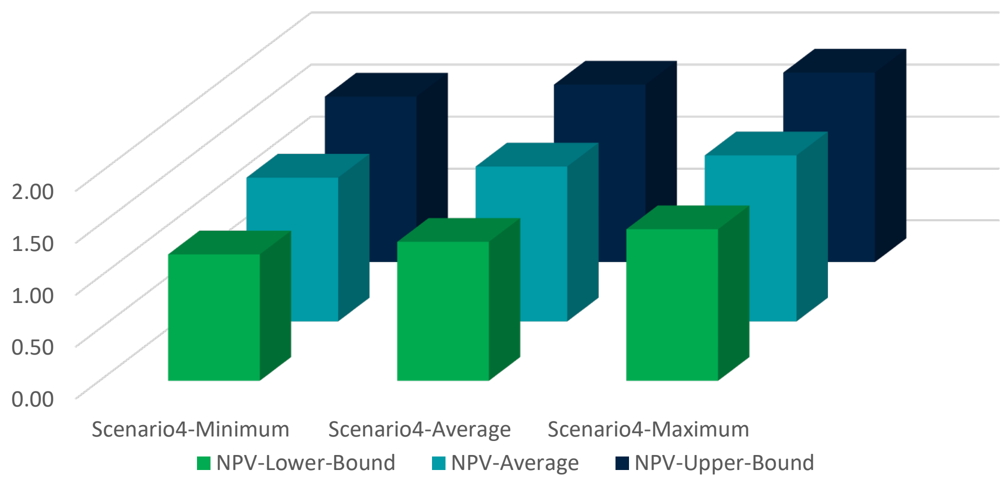
In the absence of restoration, it is assumed that limited and scattered native vegetation would grow over a 20-year period in the Aralkum. The exposed seabed might naturally develop a certain vegetation cover through primary succession with native vegetation species, mostly scattered grasses, occupying different preferential sites. The potential vegetation development is largely dependent on the available seed material and influx (e.g., through wind transportation) and the environmental conditions (e.g., soil physiochemical conditions, including available soil water, soil crust, and salinity). However, such land cover change is slow, spontaneous, and contributes little to erosion mitigation. Beyond the 20-year time horizon used in this analysis, uncertainties in predictions of vegetation cover increase. Shifts in water management might affect soil factors, while changes in climate, nature of the surface, and human activities can further influence future vegetation of the former Aral Seabed.

Figure 4.9 Annual Incremental Benefits of Restoration Compared to the Base Case (Scenario 1)



Source: Authors' estimates.

Figure 4.10 BCR for the Best-Bet Intervention of Plantation with 100% Saxaul Trees



Source: Authors' estimates.

Table 4.7: Number and Value of Lives Saved in Karakalpakstan by Using the Best Bet Practices of Planting Saxaul Trees

Item	Base Case	Best-Bet Practice (saxaul Trees on 100% of the Area)	Saving from Using Best-Bet Practice
Average of upper and lower bounds for the total value of health damages due to SDS from the Aralkum ($, million)	1.7	0.7	1.0
Share of SDS from the Aralkum in the total value of health damage due to total $PM_{2.5}$ (%)	21.8	9.1	13.0
Average of upper and lower bounds for the total number of deaths due to SDS from the Aralkum (persons)	21.2	8.8	12.4
Share of SDS from the Aralkum in the total number of deaths due to total $PM_{2.5}$ (%)	21.8	9.1	12.7
Share of Ambient Air pollution (AAP) in the total number of deaths (%)	3.0	3.0	0.0
Share of SDS from the Aralkum in total deaths (%)	0.65	0.27	0.38

Source: Authors' estimates.

5 Conclusions and Recommendations

The combination of the Aralkum's high wind speed occurrence pattern and its exposed and dry seabed surface trigger significant wind erosion. Various processes, including surface sediment "creeping," "saltation," and "suspension" contribute to soil erosion. The vast areas near the Aral Sea region have little industry and traffic pollution. Wind erosion and suspension of small sediment particles (e.g., salt, clay, and silt) are exclusive contributors to dust formation and consequently dust-sediment transport from the source areas to off-site areas beyond the dry Aral Seabed.

Event-based wind erosion modeling indicated the erosive wind speed threshold ranges between 10–15 m/s depending on the soil type. Wind speeds exceeding 10–15 m/s are expected to cause substantial erosion—noting that lower wind speeds can also cause (minor) erosion depending on the environmental conditions (e.g., soil surface structure/compound (crusting), soil moisture, and temperature). Time-series analysis using local meteorological observation datasets (spanning over the last 20 years of three-hourly wind speed data) showed that the critical wind speed criterion was reached on 16 days/year. At the same time, the biophysical wind erosion modeling shows a vast increase of sediment movement and consequential dust production with increasing wind speed. Three erosive wind classes were defined based on the local wind speed occurrence and frequency obtained from local meteorological stations (wind speed data). Due to the exponential behavior of increased wind erosion (and suspension) with increased wind speed, the prediction uncertainty of storm class 3 (highest) was accordingly large; however, because of the low occurrence probability, the overall contribution of storm class 3 events was around the magnitude of the more frequently occurring storm class 2 events. Therefore, the potential error generated through the extreme storm class 3 uncertainties may be a factor.

Combining representative wind speed classes with various rehabilitation scenarios demonstrated that the on-site "suspension" fraction of total erosion may be reduced on average by approximately 75% through vegetating the bare, dry Aral Seabed with shrubs and trees. The study considered certain landscapes that cannot be rehabilitated due to salt-crusts formed on recently desiccated and dried former seabed areas, which would reduce the overall effects from restoration efforts through planting of suitable shrub and tree species. The dry Aral Seabed continuously changes due to further shrinking of the waterbody, decrease of groundwater levels, and salt crust dynamics. The defined zoning (e.g., restorable area) reflects the most representative landscape pattern over the past 20 years (simulation period); however, ongoing change certainly impacts the zoning over time, which adds uncertainty. Similarly, potential rehabilitation efficiency by conducting one planting and sowing event was considered—as the success rate is often less than 100%. Depending on germination rate, planting method, and survival success of planted species, the replication of field replanting operations might be necessary to increase surface cover with vegetation.

Wind erosion simulations suggest that large "single object" vegetation, such as trees, should be planted in a well-designed rehabilitation approach. The planting of too few trees at large distances could exacerbate erosion by increasing local wind turbulences. Therefore, only a uniform combination of vegetation cover can achieve the desired results towards protecting the erosion prone surface, while inappropriate rehabilitation design, or a poor or scattered survival rate, can lead to adverse effects and increased erosion. Literature on dry Aral seabed rehabilitation projects (both shrub and tree-based) and related development and survival monitoring shows varied success rates; however, vegetation survival often follows a certain landscape pattern (healthy vegetation patches interrupted by larger unsuccessful planting areas), which would decrease the overall soil cover and protection functions, but would likely not generate such uniform far-distance single tree landscapes that exacerbate the erosion problem. Quasi-homogeneous patches of successful vs. unsuccessful rehabilitation areas were considered by combining different scenarios with certain percentage composition (i.e., 50% Tree (-) and 50% Tree (+)) to evaluate the resulting impacts and uncertainties through likely rehabilitation failure. The identified issues of vegetation patches development and single shrub/tree survival should be addressed in additional targeted field studies to holistically determine optimum rehabilitation approaches, considering various ecosystem synergies and economic gains, but conditioned by the desired wind-biophysical effects. The establishment of pilot sites could test the success rates of various rehabilitation approaches, from biophysical and socio-economic aspects, allowing for wind erosion occurrence and impact monitoring before advancing to large scale implementation.

The biophysical modeling study revealed potentially huge effects that annual and perennial grasses have on reducing wind erosion. Rehabilitation measures with and without grasses need to be carefully considered—outcomes of any intervention can be improved with the promotion of grass cover. As local model calibration and validation were not performed, simulation results of this study must be considered with caution. Further assessment, through e.g., field validation of grass impacts as well as investigation of the linkages between ecosystem recovery and native grass seed emergence, is highly recommended. Model-inherent uncertainties and limitations, as well as the rather unknown representation of the available model input data, need to be considered when interpreting study results.

The radial assessment model estimated the reduction of dust concentration and deposition with increasing distance to the Aralkum. The subsequent merger of modeled on-site erosion occurrence with a simple radial dispersion approach allowed the estimation of off-site dust concentration and deposition ratios. The simple radial dispersion model facilitated the on-site dust simulations and considered information on local dust deposition (including monitoring data and a remote sensing $PM_{2.5}$ spatial analysis. Both remote sensing and modeling-based approaches indicated a significant drop of dust concentrations at a distance of 100–200 km from the Aralkum (former Aral Seashore) and identified only minor Aralkum-borne dust effects at a distance of 300–500 km to the center of the dry Aral Seabed. This phenomenon is consistent with the findings in other literature (e.g., Aslanov et al., 2013).

For a planning period of 20 years, estimates show that SDS from the Aralkum cause losses to Karakalpakstan of $884 million. This study estimates on-site and off-site costs of ecosystem service loss under current conditions of approximately $44.2 million/year (equivalent to 2.1% of Karakalpakstan's GDP). The cost estimate includes: 1) on-site loss of 2.1 million tonnes of soil carbon with an estimated value of $10.3 million/year; 2) off-site impacts in terms of number of SLL equal to 21, which are valued at $1.7 million/year, as well as loss of agricultural production worth $9.9 million/year; and 3) value of forgone on-site benefits of $22.3 million/year, including carbon from above- ($5.4 million/year) and below-ground biomass ($7.3 million/year), as well as forage ($5.5 million/year) and wood ($4 million/year) that could have been harvested under the best course of action.

Planting of saxaul trees and undergrowth of grass on 100% of the area provides the highest economic return. The implementation of different intervention scenarios to restore the Aralkum can generate total annual benefits ranging between $28–44 million. About $39 million/year can be gained under the best-bet practices of planting saxaul trees and undergrowth of grass compared to the base case—equivalent to 1.9% of Karakalpakstan's GDP. The related average BCR is estimated at 1.49 for the present value of benefits and costs of the best-bet practices. This ratio may appear rather low, given that: 1) estimates were based on extremely conservative assumptions, and 2) several other damages from SDS and benefits from the restoration of the Aralkum are ignored. Therefore, the study results represent the lower-bound costs of inaction and the lower-bound benefits that can be expected from action. The results underscore the importance of careful estimation of all benefits while planning future restoration programs. This study informed a resilient forest restoration program in Uzbekistan by proving that afforestation in Uzbekistan is economically viable, yet requires careful planning and use of appropriate restoration methods to ensure that benefits are greater than the cost.

Restoration projects in Uzbekistan provide values far beyond their direct economic and financial benefits. If appropriately implemented, restoration projects in the Aralkum have the potential to deliver regional and global benefits, in addition to the economic return calculated in this study. These benefits contribute towards achievement of the NDC targets, Land Degradation Neutrality goals and the Bonn Challenge, among others. In addition, afforestation is an important part of the green-growth strategy that mainstreams climate goals and economic development. Valuation of ecosystem services, including local and global benefits, helps create a dialogue and analysis to inform climate targets in a broader development context (e.g., priority of economic recovery, jobs, etc.) which resonates with Uzbekistan's Forest Agency and, particularly, the Ministry of Finance. It also informs on-going legal and regulatory reform in Uzbekistan (Environmental Code, Forest Strategy, GHG regulation) providing quantitative measurements and thresholds for financing afforestation activity in the country.

References

An, J., Kim, S., Chang, H., Khamzina, A., and So, Y. 2018. “Vegetation Establishment Improves Topsoil Properties and Enzyme Activities in the Dry Aral Seabed, Kazakhstan.” *Forestist* 68(1): 1–6.

Aslanov, I., Opp, C. and Groll, M. 2013. “Dust Storms, Dust Transfer and Depositions in the Southern Aral Sea Region.” Annual meeting of Deutsche Bodenkundliche Gesellschaft (DBG) [the German Soil Science Society] Commission V. Conference *Soils—The Basis of Life and Responsibility*. Rostock. DBG reports. https://www.dbges.de/de.

Bennion, P., Hubbard, R., O’Hara, S., Wiggs, G., Wegerdt, J., Lewis, S., Small, I., van der Meer, J., and Upshur, R., on behalf of the Médecins sans Frontières Aral Sea Respiratory Dust and Disease Project Team. 2007 “The Impact of Airborne Dust on Respiratory Health in Children Living in the Aral Sea region.” *International Journal of Epidemiology* (36:5): 1103–1110.

Breckle, S. W. and Geldyeva, G. V. 2012. “Dynamics of the Aral Sea in Geological and Historical Times” in Breckle, S. W., Wucherer, W., Dimeyeva, L., Ogar, N., eds, “Aralkum—a Man-Made Desert.” *Springer Ecological Studies (Analysis and Synthesis)* (218): 13–35.

Buras, A., Wucherer, W., Zerbe, S., Noviskiy, Z., Muchitdinov, N., Shimshikov, B., Zverev, N., Schmidt, S., Wilmking, M., and Thevs, N. 2012. “Allometric Variability of Haloxylon Species in Central Asia.” *Forest Ecology and Management* (274): 1–9. https://doi.org/10.1016/j.foreco.2012.02.023

Chameides, W. L., Yu, H., Liu, S. C., Bergin, M., Zhou, X., Mearns, L., Wang, G., Kiang, C. S., Saylor, R. D., Luo, C., Huang, Y., Steiner, A., and Giorgi, F. 1999. “Case Study of the Effects of Atmospheric Aerosols and Regional Haze on Agriculture: An Opportunity to Enhance Crop Yields in China through Emission Controls.” *Proceedings of the National Academy of Sciences of the United States of America (PNAS)* 96(24): 13626-13633.

Costanza, R., de Groot, R., Sutton, P., van der Ploeg, S., Anderson, S.J., Kubiszewski, I., Farber, S., and Turner, R. K. 2014. “Changes in the Global Value of Ecosystem Services.” *Global Environmental Change* (26): 152–158.

Cotton, W.R., Pielke Sr., R.A., Walko, R.L., Liston, G.E., Tremback, C.J., Jiang, H., McAnelly, R.L., Harrington, J.Y., Nicholls, M.E., Carrio, G.G., and Mc Fadden, J.P. 2003. “RAMS 2001: Current Status and Future Directions.” *Meteorology and Atmospheric Physics* 82: 5–29.

Crighton, E. J., Barwin, L., Small, I. and Upshur, R. 2011. “What Have We Learned? A Review of the Literature on Children's Health and the Environment in the Aral Sea Area.” *International Journal of Public Health* (56:2): 125–138.

De Groot, R., Brander, L., van der Ploeg, S., Costanza, R., Bernard, F., Braat, L., Christie, M., Crossman, N., et al. 2012. “Global Estimates of the Value of Ecosystems and Their Services in Monetary Units.” *Ecosystem Services* 1(1): 50–61.

Dimeyeva L. 2007. “Primary Successions on the New Aral Seashore.” *Basic and Applied Dryland Research* (1): 1–16. EOSDIS Worldview. (retrieved July 9, 2020) https://worldview.earthdata.nasa.gov/?v=49.62344688107216,39.93489552182037,66.49844688107217,48.09993458432037&t=2020-03-23-T22%3A14%3A42Z.

Garrod, G. and Willis, K. 1999. *Economic Valuation of the Environment: Methods and Case Studies.* Cheltenham, UK Northampton, MA, USA: Edward Elgar.

GBD 2017 Risk Factor Collaborators. 2018. “Global, Regional, and National Comparative Risk Assessment of 84 Behavioral, Environmental and Occupational, and Metabolic Risks or Clusters of Risks for 195 Countries and Territories, 1990–2017: A Systematic Analysis for the Global Burden of Disease Study 2017.” *Lancet* 392: 1923–45.

Ge, Y., Abuduwaili, J., Ma, L. and Liu, D. 2016. “Temporal Variability and Potential Diffusion Characteristics of Dust Aerosol Originating from the Aral Sea Basin, Central Asia.” *Water, Air, and Soil Pollution* (227:63).

Golub, E. S. 2018. *Economic Analysis of Ambient Air Pollution in Poland*. Unpublished report.

Greenwald, R., Bergin, M. H., Xu, J., Cohan, D., Hoogenboom, G., and Chameides, W. L. 2006. “The influence of Aerosols on Crop Production: A Study Using the CERES Crop Model.” *Agricultural Systems* 89: 390–413.

Gregersen, H.M., Arnold, J.E.M., Lundgren, A.L. and Contreras-Hermosilla, A. 1995. *Valuing Forests: Context, Issues, and Guidelines.* FAO Forestry Paper No. 127. Rome. http://www.fao.org/3/v7395e/v7395e00.htm.

Groll, M., Opp, C. and Aslanov, I. 2013 "Spatial and Temporal Distribution of the Dust Deposition in Central Asia–Results from a Long-Term Monitoring Program." *Aeolian Research* (9): 49-62.

Groll, M., Opp, C., Issanova, G., Vereshagina, N. and Semenov, O. 2019 “Physical and Chemical Characterization of Dust Deposited in the Turan Lowland (Central Asia).” (03005) E3S Web of Conferences, CADUC 2019.

He, L., Lin, A., Chen, X., Zhou, H., Zhou, Z., and He, P. 2019. “Assessment of MERRA-2 Surface $PM_{2.5}$ over the Yangtze River Basin: Ground-Based Verification, Spatiotemporal Distribution and Meteorological Dependence.” *Remote Sensing* 11(4). doi: 10.3390/rs11040460

IAMAT. 2020. *Uzbekistan: Air Pollution | IAMAT.* (retrieved July 9, 2020) https://www.iamat.org/country/uzbekistan/risk/air-pollution

Indoitu, R., Kozhoridze, G., Batyrbaeva, M., Vitkovskaya, I., Orlovsky, N., Blumberg, D. and Orlovsky, L. 2015. “Dust Emission and Environmental Changes in the Dried Bottom of the Aral Sea.” *Aeolian Research* (17): 101–115.

Indoitu, R., Orlovsky, L. and Orlovsky, N. 2012. “Dust Storms in Central Asia: Spatial and Temporal Variations.” *Journal of Arid Environments* (85): 62–70.

INTAS and RFBR, 2001. *Assessment of the Social-Economic Damage Under the Influence of the Aral Sea Level Lowering for South Aral Sea Coast*, Vienna-Moscow-Amersfoord-Tashkent: INTAS–RFBR.

Kroeger, T. and Manalo, P. 2007. *Economic Benefits Provided by Natural Lands: Case Study of California's Mojave Desert.* https://www.defenders.org/sites/default/files/publications/economic_benefits_of_the_mojave_desert.pdf.

Kulkarni, S., Sobhani, N., Miller-Schulze, J. P., Shafer, M. M., Schauer, J. J., Solomon, P. A., Saide, P. E., Spak, S. N., Cheng, Y. F., Denier van der Gon, H. A. C., Lu, Z., Streets, D. G., Janssens-Maenhout, G., Wiedinmyer, C., Lantz, J., Artamonova, M., Chen, B., Imashev, S., Sverdlik, L., Deminter, J. T., Adhikary, B., D'Allura, A., Wei, C. and Carmichael, G. R. 2015. "Source Sector and Region Contributions to BC and $PM_{2.5}$ in Central Asia." *Meteorology and Atmospheric Physics* (15:4): 1683–1705.

Kunii, O., Hashizume, M., Chiba, M., Sasaki, S., Shimoda, T., Caypil, W. and Dauletbaev, D. 2003. "Respiratory Symptoms and Pulmonary Function Among School-Age Children in the Aral Sea Region*." Archives of Environmental Health: An International Journal* (58:11): 676–682.

Létolle, R., Aladin, N., Filipov, I., Boroffka, N.G.O., 2005. "The Future Chemical Evolution of the Aral Sea From 2000 to the Year 2050." *Mitigation and Adaption Strategies for Global Change* 10: 51–70.

Lelieveld, J., Pozzer, A. Poschl, U., Fnais, M., Haines, A., and Munzel, T. 2020. "Loss of Life Expectancy from Air Pollution Compared to Other Risk Factors: A Worldwide Perspective*." Cardiovascular Research* 116: 1910–1917.

Liu, X., Sun, H., Faike, T., Zhang, X., Shao, L., and Chen, S. 2016. *Assessing the Impact of Air Pollution on Grain Yield of Winter Wheat–A Case Study in the North China Plain.* PLoS ONE, 11(9), e0162655.

Löw, F., Navratil, P., Kotte, K., Schöler, H. F., and Bubenzer, O. 2013. "Remote-Sensing-Based Analysis of Landscape Change in the Desiccated Seabed of the Aral Sea: A Potential Tool for Assessing the Hazard Degree of Dust and Salt Storms." Environmental Monitoring and Assessment (185:10): 8303–8319.

Mamyrbayev, A., Djarkenov, T., Dosbayev, A., Dusembayeva, N., Shpakov, A., Umarova, G., Drobchenko, Y., Kunurkulzhayev, T., Zhaylybaev, M. and Isayeva, G. 2016. "The Incidence of Malignant Tumors in Environmentally Disadvantaged Regions of Kazakhstan." *Asian Pacific Journal of Cancer Prevention* (17:12): 5203–5209.

Micklin, P. P. 1988. "Desiccation of the Aral Sea: A Water Management Disaster in the Soviet Union." *Science* 241: 1170–1176.

Middleton, N., Tozer, P. and Tozer, B. 2019. "Sand and Dust Storms: Underrated Natural Hazards." *Disasters* (43:2): 390–409.

Mirzabaev, A., Goedecke, J., Dubovyk, O., Djanibekov, U., Le, Q. B., Aw-Hassan, A. 2015. "Economics of Land Degradation in Central Asia." *ZEF Policy Brief* No. 19, University of Bonn.

NASA Observatory. *Dust Storm Over the Aral Sea 2008*. http://earthobservatory.nasa.gov/NaturalHazards/view.php?id=19853.

Naseri, H., and Ahmady-Birgani, H. 2019. *Effect of Dust Deposit on the Growth and Yield of Alfalfa.* Proceedings of International Conference on Dust in Southwest Asia 23–25 April 2019. Zabol.

O'Hara, S. L., Wiggs, G. F., Mamedov, B., Davidson, G. and Hubbard, R. B. 2000 "Exposure to Airborne Dust Contaminated with Pesticide in the Aral Sea Region." *The Lancet* (355:9204): 627–628.

Opp, C., Groll, M., Aslanov, I., Lotz, T. and Vereshagina, N. 2017. "Aeolian Dust Deposition in the Southern Aral Sea Region (Uzbekistan): Ground-based monitoring results from the LUCA project." *Quaternary International* (429): 86–99.

Orlovsky, L. 2011. *Long term ecological research program for monitoring aeolian soil erosion in Central Asia.* CALTER Project Executive Summary, Version 1. INCO-CT-2005-516721. https://cordis.europa.eu/docs/results/516/516721/127976601-19_en.doc.

Orlovsky, N. and Orlovsky, L. 2001. "White Sandstorms in Central Asia" in UN, *Global Alarm: Dust and Sandstorms from the World's Drylands*. Bangkok: United Nations. 2001:169–201.

Pielke, R.A., Cotton, W.R., Walko, R.L., Tremback, C.J., Lyons, W.A., Grasso, L.D., Nicholls, M.E., Moran, M.D., Wesley, D.A., Lee, T.J., and Copeland, J.H. 1992. "A Comprehensive Meteorological Modeling System RAMS." *Meteorology and Atmospheric Physics*. 49 (1-4): 69–91.

Quillérou, E., Thomas, R.J., Guchgeldiyev, O., Ettling, S., Etter, H., and Stewart, N. 2016. *Economics of Land Degradation (ELD) Initiative: Broadening Options for Improved Economic Sustainability in Central Asia.* Synthesis Report. Report for the ELD Initiative from the Dryland Systems Program of CGIAR c/o ICARDA, Amman, Jordan. (retrieved November 26, 2019) http://www.eld-initiative.org/fileadmin/pdf/ELD_CA_regional_report.pdf.

Reid, W.V., Mooney, H.A., Cropper, A., Capistrano, D., Carpenter, S.R., Chopra, K., Dasgupta, P., Dietz, T., Duraiappah, A.K., Hassan, R. and Kasperson, R., 2005. *Ecosystems and Human Well-being-Synthesis: A report of the Millennium Ecosystem Assessment.* Washington DC: Island Press.

Rospotrebnadzor. 2018. "Maximum Allowable Concentration (MAC) of Ambient Air Pollutants in Urban and Rural Residential Areas." *Hygiene guidelines GN 2.16.3492-17* with modifications. Moscow: Federal Center of Hygiene and Epidemiology (retrieved September 12, 2020) https://files.stroyinf.ru/Data2/1/4293740/4293740240.pdf.

SanPiN. 2011. *Hygiene Standards List of Maximum Allowable Concentrations (MAC) of Pollutants in Ambient Air of Residential Areas in Republic of Uzbekistan* №0293-11, dated May 16, 2011. Research Institute of Sanitary Guidelines, Rules, and Hygiene standards. Tashkent: Ministry of Health of Republic of Uzbekistan.

Semenov, O. E. 2012. "Dust Storms and Sandstorms and Aerosol Long-Distance Transport," in Breckle, S. W., Wucherer, W., Dimeyeva, L., and Ogar, N., eds, "Aralkum–A Man Made Desert." *Springer Ecological Studies (Analysis and Synthesis)* (218): 73–82.

Shen, H., Abuduwaili, J., Ma, L. and Samat, A. 2019. "Remote Sensing-Based Land Surface Change Identification and Prediction in the Aral Seabed, Central Asia." *International Journal of Environmental Science and Technology* (16:4): 2031–2046.

Smeets, T. 2020. *Impact of vegetation on Aeolian dust transport in the Aralkum.* Master Thesis at Utrecht University, the Netherlands.

Spivak, L., Terechov, A., Vitkovskaya, I., Batyrbayeva, M. and Orlovsky, L. 2012. "Dynamics of Dust Transfer from the Desiccated Aral Sea Bottom Analyzed by Remote Sensing." in Breckle, S. W., Wucherer, W., Dimeyeva, L., and Ogar, N., eds, "Aralkum–A Man-Made Desert." *Springer Ecological Studies (Analysis and Synthesis)* (218): 97–106.

Thevs, N., Wucherer, W., & Buras, A. 2013. "Spatial Distribution and Carbon Stock of the Saxaul Vegetation of the Winter-Cold Deserts of Middle Asia." *Journal of Arid Environments* 90: 29–35. https://doi.org/10.1016/j.jaridenv.2012.10.013.

Tilahun, M., Singh, A., Kumar, P., Apindi, E., Schauer, M., Libera, J. and Lund, H.G. 2018. *The Economics of Land Degradation Neutrality in Asia: Empirical Analyses and Policy Implications for the Sustainable Development Goals.* (retrieved May 4, 2020) https://www.eld-initiative.org/fileadmin/pdf/Asia_Report_EN.pdf.

Twigg, J. 2001. *Sustainable Livelihoods and Vulnerability to Disasters.* Benfield Hazard Research Centre for the Disaster Mitigation Institute.

UN. 2001. *Global Alarm: Dust and Sandstorms from the World's Drylands.* Bangkok: United Nations: 345.

UNEP, WMO, UNCCD. 2016. *Global Assessment of Sand and Dust Storms.* Nairobi: United Nations Environment Programme (UNEP).

UNESCAP. 2018. *Sand and Dust Storms in Asia and the Pacific: Opportunities for Regional Cooperation and Action.* United Nations Economic and Social Commission for Asia and the Pacific (UNESCAP), Bangkok. ST/ESCAP/2837.

Van Ittersum, M.K. and Cassman, K. 2013. "Yield Gap Analysis—Rationale, Methods and Applications—Introduction to the Special Issue." *Field Crops Research* 143: 1–3. http://dx.doi.org/10.1016/j.fcr.2012.12.012.

WHO. 2006. *Air Quality Guidelines for Particulate Matter, Ozone, Nitrogen Dioxide and Sulfur Dioxide. Global update 2005. Summary of Risk Assessment*. Geneva: World Health Organization (WHO). (retrieved September 12, 2020) https://apps.who.int/iris/bitstream/handle/10665/69477/WHO_SDE_PHE_OEH_06.02_eng.pdf?sequence=1.

Wiggs, G. F. S., O'Hara, S. L., Wegerdt, J., Van Der Meer, J., Small, I., and Hubbard, R. 2003. "The Dynamics and Characteristics of Aeolian Dust in Dryland Central Asia: Possible Impacts on Human Exposure and Respiratory Health in the Aral Sea Basin." *The Geographical Journal* (169:2): 142–157.

Wolfe, S. A. and W. G. Nickling, 1993. "The Protective Role of Sparse Vegetation in Wind Erosion." *Progress in Physical Geography* 17(1): 50–68.

World Bank. 1998. "Aral Sea Basin Program (Kazakhstan, Kyrgyz Republic, Tajikistan, Turkmenistan, and Uzbekistan) Water and Environmental Management Project." *World Development Sources*, WDS 1998-3. Washington, DC: World Bank.

World Bank. 2014. *Turn Down the Heat: Confronting the New Climate Normal.* Washington, DC: World Bank.

World Bank Group. 2019. *State and Trends of Carbon Pricing 2019.* Washington, DC: World Bank.

Wucherer, W., Breckle, S. W., and Buras A. 2012a. "Primary Succession in the Aralkum" in Breckle, S. W., Wucherer, W., Dimeyeva, L., and Ogar, N., eds, "Aralkum–A Man-Made Desert." *Springer Ecological Studies (Analysis and Synthesis)* (218): 161–198.

Wucherer, W., Breckle, S. W., Kaverin, V. S., Dimeyeva, L. A. and Zhamantikov, K. 2012b. "Phytomelioration in the Northern Aralkum" in Breckle, S. W., Wucherer, W., Dimeyeva, L., and Ogar, N., eds, "Aralkum–A Man-Made Desert." *Springer Ecological Studies (Analysis and Synthesis)* (218): 343-386.

Yigezu, Y.A., Akramkhanov, A., T. Ergasheva, A., Juraev, M., and Ergashev. 2019. *Costs of Environmental Degradation in the Mountains of Tajikistan.* Washington DC: World Bank Group. https://documents.worldbank.org/en/publication/documents-reports/documentdetail/789791609753275902/costs-of-environmental-degradation-in-the-mountains-of-the-republic-of-tajikistan

Zia-Khan, S., Spreer, W., Pengnian, Y., Zhao, X., Othmanli, H., He, X., and Muller, J. 2015. "Effect of Dust Deposition on Stomatal Conductance and Leaf Temperature of Cotton in Northwest China." *Water* (7): 116–131.

Annex A: Assessment of the Aral Seabed Rehabilitation Approaches and Scenarios

The effects of vegetation-based rehabilitation of the dry Aral Seabed on protecting the erodible sediments from the wind-induced movement are controlled by the on-site environmental conditions (actual soil erodibility) and the selected rehabilitation measures (out-planted and successively developed vegetation cover). During this study, an expert team consisting of national and international scientists discussed and agreed on a set of target rehabilitation options to investigate further. The actual on-site environmental conditions, as well as the selected rehabilitation scenarios are described in Table 3.1 based on local knowledge and data obtained from reference pilot sites established in the Aralkum. Biophysical simulation models were used and set up, reflecting defined and locally proven rehabilitation measures and development stages. The simulations tackle impacts of implementation at scale and trade-offs between on-site and off-site areas to the south of the former Aral Sea. Compromising between explicit results and covering a wider range of impacts of potential rehabilitation measures and stages, the work focused on three scenarios with upper and lower ranges, representing a total of six scenarios simulated and spatially combined at a later stage (Annex Table A.1).

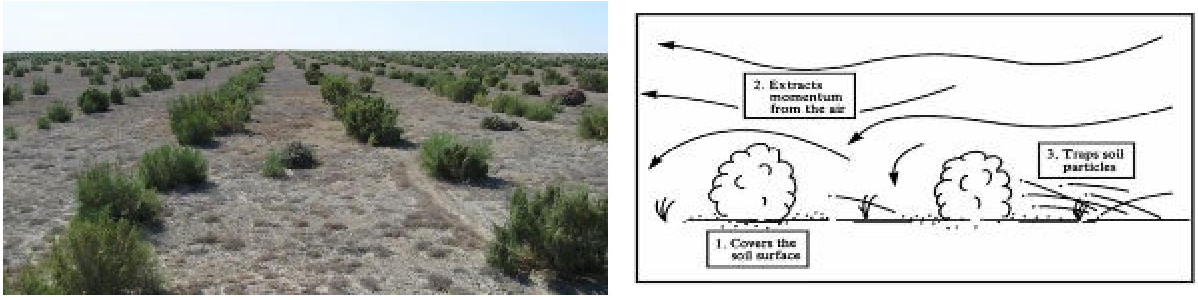
Annex Table A.1 Scenario Overview: Degraded Status vs. Rehabilitation Through Shrub and Tree Plantations

Environmental Condition	Scenario	Scenario Description (vegetation cover)	Expected Model Output (notes)
Degraded (present condition)	Bare (-)	Bare Represents: recently dried-up areas with no vegetation cover (highest vulnerability)	**Present:** most erosion susceptive scenario (worst case)
	Bare (+)	Bare, with marginal grass cover Represents: older dried up areas with a limited degree of natural vegetation emergence (few bunch grasses)	Present: slightly reduced erosion susceptivity (checking the upper range of proneness to wind erosion)
Rehabilitated Shrubs (shrub-based intervention)	Shrub (-)	Represents: out-planted shrubs with marginal or absent natural recruitment (pure shrub out-planting effect)	Limited reduction of erosion (minimum of erosion resistance through human interventions, e.g., shrubs; the lower boundary of rehabilitation impact range)
	2. Shrub (+)	Shrub cover: rehabilitated (Salsola or Atriplex) incl. recruitment and grasses Represents: Out-planted shrubs with specific extent recruitment and grass cover	Reduction of erosion (checking the significance of human intervention vs. natural recruitment)
Rehabilitated Trees (tree-based intervention)	Tree (-)	Tree cover: rehabilitated (Saxaul) Represents: out-planted trees with marginal or absent natural recruitment (pure tree out-planting effect)	Limited reduction of erosion (minimum of erosion resistance through human interventions (trees); the lower boundary of rehabilitation impact range and check vs. shrub intervention)
	Tree (+)	Represents: out-planted trees with specific extent recruitment, shrub, and grass cover (highest cover scenario)	Highest reduction of erosion through three different layers: 1) trees, 2) shrubs, and 3) grasses (checking the significance of human intervention vs. natural recruitment)

Scenario 1.1 Bare (-) and Scenario 1.2 Bare (+) represent actual dry seabed conditions, while rehabilitation Scenario 2.1 Shrub (-), Scenario 2.2 Shrub (+), Scenario 3.1 Tree (-), and Scenario 3.2 Tree (+), represent potential out-planting of native shrub and tree species. For on-site wind erosion modeling, the selected

vegetation options represent obstacles to the driving force wind, which create friction—e.g., energy dissipation through turbulence—(Annex Figure A.1). The wind obstacles depend on the vegetation size, density/extent, and spatial distribution. The scenarios with (+) include the emergence of native vegetation (e.g., grasses) facilitated through the shelter of primarily out-planted species or natural regeneration and succession. All scenarios are based on field observations and expert knowledge and reflect realistic stages achievable with the Aralkum.

Annex Figure A.1 Vegetation-Based Rehabilitation Effects: Obstacles to Wind Erosion



Source: http://livingasia.online/aralsea/uz_kaz (left); Wolfe and Nickling (1993) (right).

Wind Erosion and Dust Assessment: Soil Detachment and Air Pollution

Wind speed is the driving force of top-soil movement, erosion, and, consequently, the detachment and uptake of small sediment particles into suspension, as well as their dispersion and transportation to off-site areas. To analyze erosion and dispersion processes, the assessment of the on-site (Aralkum) wind speed occurrence and frequency pattern is key, as it helps to narrow down the most important conditions and consequentially to define critical events without simulation of long-period sub-daily processes that are computer-intensive.

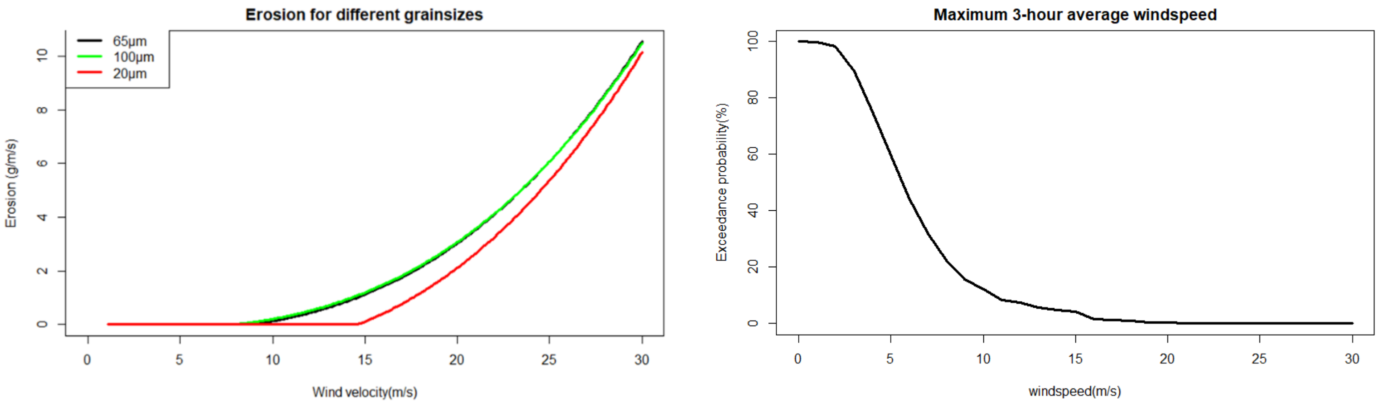
On-Site Driving Force: Assessment of Wind and Erosion Occurrence

Time-series analysis of wind parameters (speed, direction) reveals the occurrence and frequency pattern of wind as a driving force, while threshold analysis identifies potential erosive events. Wind speed data is coupled with biophysical wind erosion simulations to investigate the most critical wind speed for the initiation of sediment movement. For the wind speed threshold analysis, Scenario Bare (-) represents the most vulnerable surface conditions, independent of the existence of less erosion-prone environmental patches within the Aral Seabed. The Scenario Bare (-) prevalence is likely to cause erosion when local wind speeds exceed the critical threshold. The biophysical model-based investigation of Bare (-) was pursued under local surface soil heterogeneity to define upper and lower erodibility conditions. The soils' conditions were obtained from published reports. Annex Figure A.2 shows the erosion threshold analysis considering different soil types (soil texture). The pre-analysis of the dry Aral Seabed erodibility resulted in the following findings:

1. Various soil textural conditions present in the dry Aral Seabed have different susceptibility to erosion—especially in terms of sediment movement magnitude with increasing wind speed.
2. Various soil compaction stages (bulk density) have minor effects. However, surface crusting effects need to be addressed through expert opinion as the field visit could not be undertaken due to COVID-19.
3. Various soil conditions present in the dry Aral Seabed (both texture and density) have a similar overall threshold of erosion initiation—estimated at 10–15 m/s wind speed (Annex Figure A.2).

In this study, the wind speed threshold was set to 15 m/s (based on Annex Figure A.2 and literature analyses). This threshold will be higher in areas with soil crust (e.g., salt crust in proximity to Aral water bodies) and/or the presence of surface obstacles such as vegetation cover. The 15 m/s critical wind speed is related to overall low–medium sediment movement and dust production. Potential erosion occurring at lower wind speeds (e.g., 5–15 m/s) is minor in this study and its effect restricted to immediate surroundings only. Annex Figure A.2 demonstrates that soil erosion greatly increases with higher wind speeds and, therefore, higher wind speeds might dominate sediment movement processes. However, time-series analysis was required to disclose the occurrence, frequency, and magnitude of wind speeds that are larger than the defined threshold (Annex Figure A.2, right). Annex Figure A.2 shows the wind speed occurrence distribution as an exceedance graph, which indicates that less than 10–20% of the three-hourly wind speeds exceed the critical threshold values (10–15 m/s).

Annex Figure A.2 Erosion Threshold Analysis Using Flat and Uncovered Terrain Bare (-) Scenario for Different Soil Types Present in the Dry Aral Seabed



Source: Authors' estimates.
Note: Sediment movement under dry initial soil conditions starts between 10–15 m/s wind speed (left). Three-hour wind speed occurrence in the dry Aral Seabed based on observations from Kungrad meteorological station, located near the southwest border of the Aralkum (right).

Frequency analysis of potentially erosive events was used to define three storm severity classes. The storm severity classification relates to the maximum three-hourly wind speed recorded at a specific day, classified as:

Storm class 1: maximum three-hourly wind speed > 15 m/s (15–20 m/s);

Storm class 2: maximum three-hourly wind speed > 20 m/s (20–25 m/s); and

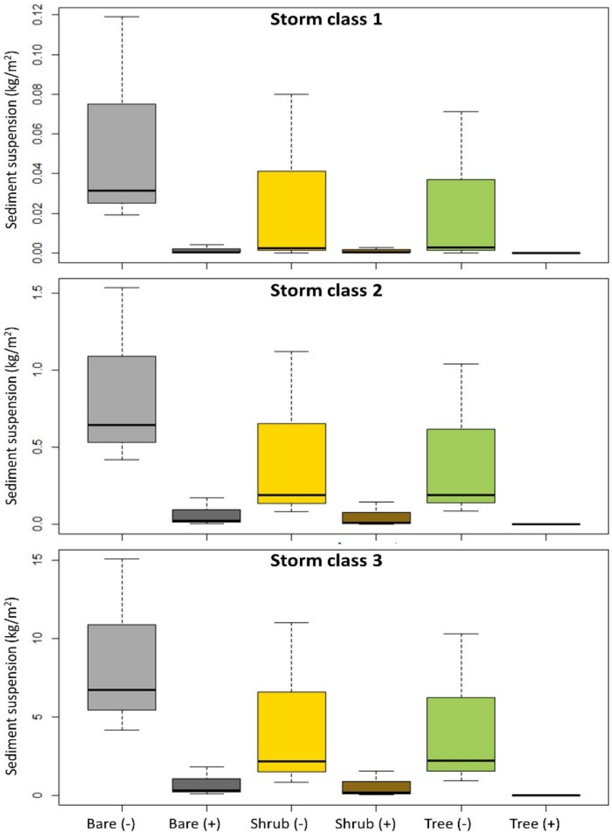
Storm class 3: maximum three-hourly wind speed > 25 m/s.

The three storm severity classes were analyzed according to: i) their overall occurrence across the Aralkum (potentially erosive events); ii) their occurrence during highly erodible soil states (based on pre-event meteorological conditions such as rainfall and temperature); and iii) storm occurrence during highly erodible soil states with target wind direction (towards southern target area). Potentially erosive wind speeds occurring during wet or frozen soil conditions—related to surface soil protection and/or low erodibility effects during such conditions—were removed. For subsequent SDS simulation, Class 3 storm events were particularly important.

Data from meteorological stations suggests that in the last 20 years (spring 2000–summer 2020) on average, the wind speed threshold was exceeded 16 days/year. However, only 9.4 erosive event days/year occurred due to favorable conditions such as dry soil, predominant wind directions from east, northeast, west, and northwest. The data matches with aerosol observations reported by Spivak et al. (2012), recorded on average 13 SDS event days/year between 2000 and 2009.

Simulation of storm classes 1–3 for various vegetation scenarios using the wind erosion simulation model (Smeets, 2020) indicated specific sediment suspension distribution (Annex Figure A.3) with a fraction of fine particles (mostly silt and clay) suspended above the ground. Coarser sediment particles (e.g., sand) might move through "saltation" processes only and are not dispersed into the higher above-ground layers for transport to off-site areas.

Annex Figure A.3 Daily Event Distribution of Sediment Suspension Loads per SDS Class and Scenario



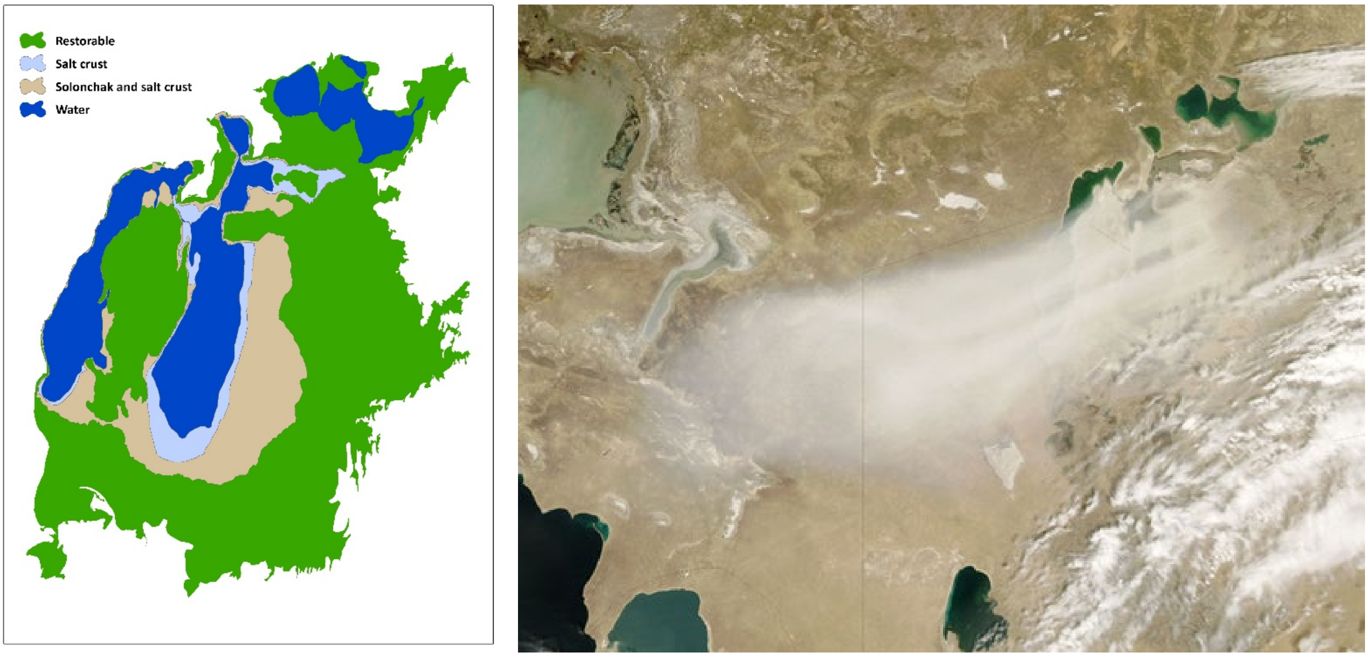
Source: Authors' estimates.

Annex Figure A.3 indicates clear effects of the out-planted vegetation (scenarios Shrub and Tree) on reducing sediment suspension. Differences between Bare (-) and Bare (+) scenarios are based on grass cover, which, according to local experts, is present in some locations of the Aralkum. For subsequent dispersion modeling and transport to off-site areas, diverse options of current landscape pattern, e.g., a combination of Bare (-) and Bare (+) mosaic), as well as potential landscape with rehabilitation options consisting of both low and well-performing areas, e.g., a combination of Shrub (-) and Shrub (+), and Tree (-) and Tree (+) mosaics, were considered. The team defined most scenario combinations using a 50% spatial distribution of both (-) and (+) scenarios.

Off-Site Effects: Transportation and Dispersion of Dust

Off-site transportation of dust (suspension fraction of the on-site model) is a two-step process. First, a simple empiric model was set up considering wind speed and direction to model all class 1–3 storms that occurred in the last 20 years (observation period: spring 2000–summer 2020). The empiric model considers various zones of the Aralkum (Annex Map A.1) covering the target area (Annex Map A.1) from the center of the Aralkum in circular buffer zones (100–200, 200–300, and 300–500 km) to the south. The model considers various dispersion factors and estimates the radial suspension movement as a function of the distance from the source area (Aralkum) and the settling fraction of sediments. The model provides radial (spatial) information on average and peak dust concentrations ($PM_{2.5}$) as well as on seasonal and long-term dust cumulation. Both parameters are important; dust concentration (in the air) was used for consecutive human health related assessment, while dust cumulation (on the ground), over time, was defined as the dominant cause for agricultural production decline. However, the model does not consider wind trajectory changes along the SDS pathways, as shown in the satellite image (Annex Map A.1)), adding a significant source of uncertainty. Although the model is simplistic, it was preliminarily adjusted (hand-calibrated) to various sediment accumulation datasets (observations) obtained from the literature. Actual stage off-site effect assessment is based on the first-step simplistic model solely at this stage.

Annex Map A.1 The Aral Sea Zoning (Left) and Satellite Image of an SDS Sourcing from the Aralkum (Right)



Source: Map constructed by authors (left); https://worldview.earthdata.nasa.gov/ (right).
Note: The water body (left) reflects the median area during the observation period 2000–2020 to represent average on-site conditions over the entire target simulation period.

In the second step, the Regional Atmospheric Modeling System (RAMS) (Cotton et al., 2003; Pielke et al., 1992) was used to simulate selected events from storm classes 1–3 to generate physically sound SDS trajectory simulations. Despite more accurate outputs provided by the RAMS model with the use of atmospheric-physical laws, the limited computation power and resources available restricted an in-depth analysis of the entire 2000–2020 period atmospheric dynamics. Because the RAMS model requires a broad spatial array (several thousand km) of explicit knowledge of its environment, its use was limited to specifically selected event simulation only. Outputs of the RAMS model feed into the simplistic empirical model assessment towards a blended product for spatial SDS impact assessment within the Aralkum. Results of RAMS analyses are expected to be integrated in follow up studies.

Concentration of $PM_{2.5}$ in the Study Area

National Aeronautics and Space Administration Global Modeling and Assimilation Office (NASA GMAO) provides global coverage of air pollution data that includes variables to calculate $PM_{2.5}$. The latest atmospheric reanalysis produced by the Modern-Era Retrospective Analysis for Research and Applications, Version 2, (MERRA-2) provides long-term (1980–present) record of global atmospheric analyses, with a detailed list of variables described by He et al. (2019). Air pollution dataset for any location is accessible via Data and Information Services Center (DISC). [17] Based on variables estimated by MERRA-2, $PM_{2.5}$ is calculated by the following equation:

$$PM_{2.5} = 1.375 \times SO_4 + 1.6 \times OC + BC + Dust_{2.5} + SS_{2.5}$$

Where, SO_4, OC, BC, $Dust_{2.5,}$ and $SS_{2.5}$ represent sulfate, organic carbon, black carbon, dust, and sea-salt particulate matter with a diameter of less than 2.5 μm respectively. More details and description is provided in Annex Map A.1.

[17] https://disc.gsfc.nasa.gov/

Economic Valuation of Selected Ecosystem Services

General Framework

Knowing the on-site erosion and dust mobilization and transport to off-site affected areas, and simulation of on- and off-site ecosystem services inform decision making on the suitability of land rehabilitation in the dry Aral Seabed. Reduction of sediment load transported from the dry Aral Seabed as a result of the established vegetation cover is one ecosystem service benefit. At the same time, the vegetation-based rehabilitation of marginal land increases the variety of ecosystem services—with different assessment complexity and pre-estimated value. Specific ranking, based on local and international expert knowledge, was undertaken to select the most suitable on- and off-site ecosystem services to be considered in this study.

Most economic valuations of land degradation are made in comparison to a scenario with no-land degradation. This implicitly assumes that after the interventions, land will be restored to 100% of its potential (Quillérou et al., 2016). We argue that these assumptions are not realistic as it is difficult, if not impossible, to know the land attributes if degradation would not have taken place (the counterfactual). As argued by Quillérou et al. (2016), interventions may not restore land to its original state and, therefore, the benefits of action and the costs of inaction may be overestimated.

Following Yigezu et al. (2019), we apply the concept of yield gap analysis (van Ittersum and Cassman, 2013) for the quantitative estimation of land use-values, natural and environmental resources, and other assets. In this study, the loss of land value and other assets affected by SDS is estimated as the difference between the value of ecosystem services of land in other areas with similar social, economic, biophysical, and other conditions, but not affected by SDS, and the value of the ecosystem services in the affected areas (van Ittersum and Cassman, 2013) for the quantitative estimation of land use-values, natural and environmental resources, and other assets. In this study, the loss of land value and other assets affected by SDS is estimated as the difference between the value of ecosystem services of land in other areas with similar social, economic, biophysical, and other conditions, but not affected by SDS, and the value of the ecosystem services in the affected areas.

To determine the economic cost of SDS and the economic benefits of the proposed mitigation measures, it is essential to identify natural and environmental resources as well as other assets that are affected by SDS and the associated losses/gains in social, economic, and environmental benefits. Different components of the total economic value of land can be estimated using a variety of valuation methods, which can be classified as market and non-market demand-based economic valuation methods. In this study, we use a combination of the market and non-market valuation methods to attach monetary values to different natural and environmental resources, as well as other assets that are adversely affected by SDS. Where markets for the resource or its services exist, assessment is straightforward. An example would be a local real estate market. Observations on the number and value of transactions provide information about the people's willingness to pay for land and the quantity of land changing hands. These market data provide means through which to deduce the market demand curve and the actual payments made during a given period. Market demand-based methods include the revealed and stated preference methods. In the revealed preference method, the value of an ecosystem service is measured in terms of the market price for that service in the market, or indirectly by examining the purchase of a related service (complementary or substitute service) in the private marketplace (Garrod and Willis, 1999). Tilahun et al. (2018) provide a detailed description of the different methods available for the valuation of natural resources and environmental assets.

Estimation of Economic Cost of SDS

This study provides a first attempt to assess impacts of SDS from the Aralkum. SDS can have adverse effects on public health, crop and woody biomass productivity, infrastructure, and land and air transport. Therefore, the quantification and valuation of impacts are based on broad categories, including nature, scale, spatial and temporal coverage, frequency and intensity of effects identified in the previous section. Estimation of SDS effects and the monetary value of these impacts were generated based on the following steps:

1. Delineate the affected area.
2. Using $PM_{2.5}$ values to classify the ambient air pollution (AAP) level in each district.
3. Use results of the dispersion model to determine the level of dust deposited by SDS originating from the dry Aral Seabed.
4. Classify districts based on their susceptibility to impacts of SDS. As a result, districts within 100–200 km from the center of the Aral Seabed are classified as high impact, while those between 200–300 km and 300–500 km as medium, and low impact, respectively.
5. Identify affected biophysical, socio-economic, and ecosystem services. Develop a priority list to identify services that are significant and relevant with respect on-site and off-site effects. From on-site effects, we consider the value of soil eroded by wind and the opportunity cost of forest that could have been planted on the vast land of the Aralkum Desert, which could serve as an important carbon sink. For off-site impacts, we consider health and crop production impacts.
6. Develop a list of relevant impact indicators for each of the prioritized ecosystem services, crop production and health impacts.
7. Determine the per-unit or percentage effects (e.g., per person, per hectare, per district, etc.) of SDS on the different biophysical and socio-economic indicators (i.e., yield, health, and soil erosion) across distinct levels of effects, taking the difference between the condition in the least affected districts and the corresponding districts in the highly and moderately affected areas. For the on-site effects, we first defined four different scenarios based on Table 3.1. Scenario 1 (which represents the current scenario) is defined as a combination of scenarios 1.1 and 1.2, e.g., 90% Bare (-) and 10% Bare (+). Scenario 2 is defined as a combination of scenarios 2.1 and 2.2, e.g., 50% Shrub (-) and 50% Shrub (+). Scenario 3 is defined as a combination of scenarios 3.1 and 3.2, e.g., 50% Tree (-) and 50% Tree (+). Finally, we define Scenario 4 as the best scenario which assumes full implementation of Scenario 3.2. e.g., 100% Tree (+). Subsequently, a comparison was made based on simulation results between the best-practice (Scenario 4) and the remaining scenarios, including the base case (i.e., Scenario 1 representing the current condition). For health impacts, we followed Golub (2018) to estimate the number of statistical lives lost (SLL) due to SDS from the Aralkum using relative risk figures obtained from the global burden of diseases study (GBD 2017 Risk Factor Collaborators). The relative risk function is defined as the ratio of the probability of a health outcome occurring in an exposed group to the probability of it occurring in a non-exposed group. GBD 2017 Risk Factor Collaborates presents relative risks within uncertainty intervals. District level 2019 data of mortality was collected for six diseases (ischemic heart disease, stroke, lung cancer, chronic obstructive pulmonary disease, lower respiratory illness, diabetes mellites type 2) and the value of morbidity was assumed to be 10% of the value of mortality.
8. Obtain district-wise data on population size, crop areas, yield, and regional GDP for each area classified as high, moderate or low impact.
9. Obtain prices of major crops, international carbon price, and Value of Statistical Life (VSL).
10. Generate the aggregated value of SDS impacts for each class of affected areas as the product of per-unit value of impacts and the population size/total area affected in each class.
11. Sum the value of impacts across all three classes of affected areas to obtain the total provincial cost of SDS originating from the Aralkum.

Valuation of On-Site and Off-Site Costs and Benefits for Alternative Intervention Scenarios and Identification of the Scenario with the Highest Net Return

1. The following is required to determine the values of benefits derived from the proposed alternative interventions:

2. Identification of the land, natural and environmental resources, other assets, and socio-economic parameters (Annex Table A.2), and their qualities, quantities or values which are affected by alternative interventions;

3. Estimation of annual economic benefits of land, natural and environmental resources, and other assets, and socio-economic parameters under current conditions, e.g., Scenario Bare (-) to serve as the counterfactual;

   Estimation of annual economic benefits of land, natural and environmental resources, and other assets, and socio-economic parameters under alternative intervention scenarios. These values are generated for each of the three categories of effects (i.e., on-site effects on soil carbon, off-site effects on crops, and off-site effects on health).

   The economic benefits of each alternative intervention are estimated as the difference between step (3) and (2) above. The intervention with the highest net benefit is equal to the largest difference between the economic benefits of the intervention (3) and the economic cost of implementing the intervention.

Annex Table A.2 Reported Success Rates of Tree Planting (Restoration) Depending on the Agro-ecologies (Based on the Literature Review)

Location of Impact	Increase Per Year	90% Bare (-) and 10% Bare (+)	50% Shrub (-) and 50% Shrub (+)	50% Tree (-) and 50% Tree (+)	Scenario 4 100% Tree (+)
On-site	Soil Carbon, t/ha				
	Carbon from biomass (above ground), t/ha				
	Carbon from biomass (below ground), t/ha				
Off-site	Cropland (all crops) yield + quality				
	Health Cost Avoided				

Robustness of the Analysis

Robustness of the analysis is ensured using lower-bound, average, and upper-bound estimates for each scenario that reflect success rates for tree planting. These bounds are estimated using the literature review reflected in Annex Table A.3.

Annex Table A.3 Reported Success Rates of Tree Planting (Restoration) Depending on the Agro-ecologies (Based on the Literature Review)

	Min	Av	Max	Deviation from the Mean (%)		
	5.00	8.50	12.00	41%	Seed emergence rate in soils, can be improved to reach 28% with proper agrotechnology. New collected seeds have laboratory emergence rate 92–94%	Dimeeva and Permitina, 2006
	76.00	87.00	98.00	13%	Seashore sandy soils, saplings/seedlings	Dimeeva 2011; Dimeeva and Permitina, 2006
	17.63	37.00	56.37		Near seashore slightly saline soils with sand layer brought by wind, saplings	Dimeeva, 2011; Dimeeva and Permitina, 2006
	12.00	13.00	14.00	8%	Near seashore light and highly saline loamy soils, seedlings. Improved methods improved survival rate by 26 times	Dimeeva, 2011; Dimeeva and Permitina, 2006
	8.10	17.00	25.90		Saplings, experimental plots in north seabed, sandy soils	Dimeeva, 2011
	10.00	50.00	90.00	80%	Saplings, experimental plots in north seabed, sandy soils	Dimeeva, 2011
	1.00	7.50	14.00	87%	Dry year 54mm, saplings	Dimeeva, 2011
	13.00	22.50	32.00	42%	Wet year 260mm, saplings	Dimeeva, 2011
	0.00	32.00	64.00	100%	Areas with heavy lithology, seedlings and seeds, good on sandy and loamy sand areas	Dimeeva and Permitina, 2006
	46.00	47.50	49.00	3%	Heavy soils, spring planting	Dimeeva and Permitina, 2006
	8.00	16.00	24.00	50%	Saline loamy soils, planted seedlings in sand accumulating ditches	Dimeeva and Permitina, 2006
	0.44	0.92	1.40		Saline soils, seedling planted manually in pits with add sand layer	Dimeeva and Permitina, 2006
	9.53	20.00	30.47		Saline soils, planting in deep ditches, saplings	Dimeeva and Permitina, 2006
	28.59	60.00	91.41		GIZ project, seedlings, summarized average survival rate for saxaul and selin (Aristida karelini)	Navratil and Wilps, 2009
	0.00	23.50	47.00	100%	Ditches, data from control plots without soil amendments	Kabanov et al., 2017
Average	**15.69**	**25.07**	**43.30**	**52%**		

Note: 85% of the actual average is utilized in the study for a conservative estimation of the impacts of interventions.

Annex B: Air Pollution: Data Source and Preparation

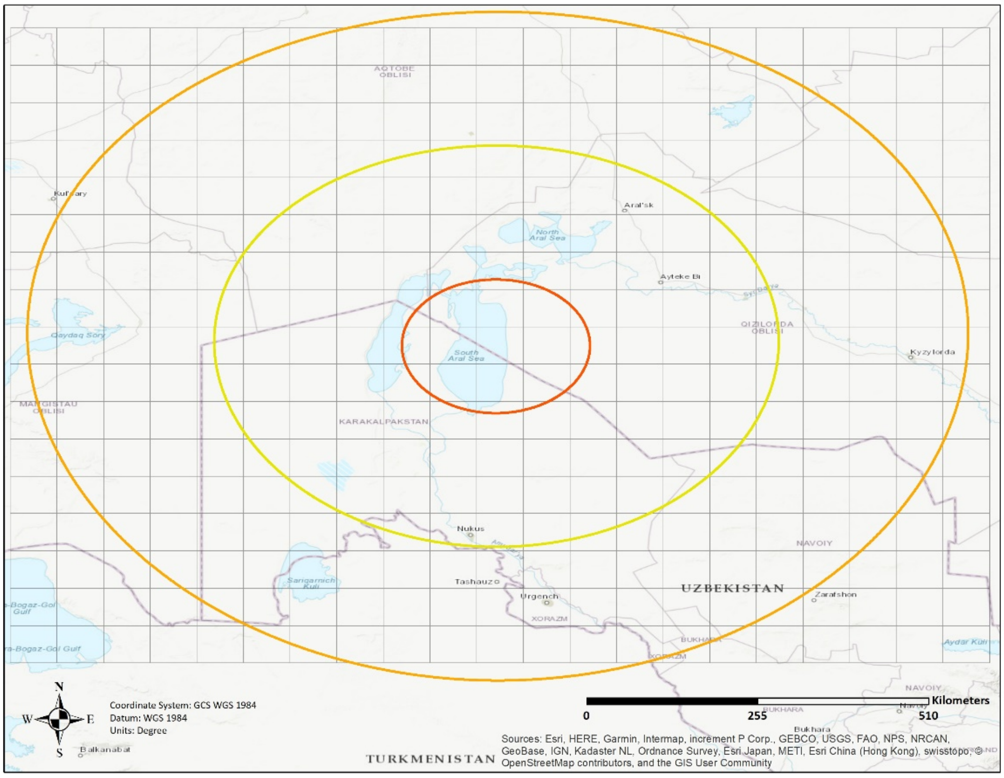
The latest atmospheric reanalysis of the modern satellite era produced by NASA's Global Modeling and Assimilation Office (GMAO) is the Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2). MERRA-2 is a long-term record of global atmospheric analyses that provides the newly-released product values of daily Particulate Matter with diameter ≤ 2.5 μm ($PM_{2.5}$) and other data from 1980 and thereafter. The list of variables can be explored in He et al. (2019). The data can be accessed from the Modeling and Assimilation Data and Information Services Center (MDISC) available on the Goddard Earth Sciences (GES)—Data and Information Services Center (DISC) website: https://disc.gsfc.nasa.gov/. The $PM_{2.5}$ data are calculated by the following equation:

$$PM_{2.5} = 1.375 \times SO_4 + 1.6 \times OC + BC + Dust_{2.5} + SS_{2.5}$$

Where SO_4, OC, BC, $Dust_{2.5}$, and $SS_{2.5}$ represent sulfate, organic carbon, black carbon, dust, and sea-salt particulate matter with a diameter of less than 2.5 μm, respectively. The MERRA-2 reanalysis does not include nitrate particulate matter, which is primarily emitted by vehicle exhaust and industrial production, leading to biases compared with ground measurements (He et al., 2019).

A buffer zone of a 500-km radius from the center of the Aral Sea was selected to clip and download the dust surface mass concentrations—$PM_{2.5}$ (DUSMASS25) in kg/m^3 for the period from Jan 1, 1980 to April 29, 2020. A total of (14,729) files were downloaded in netCDF-4 format and combined into one NetCDF file using "NetCDF Operators" (NCO) and "Climate Data Operators" (CDO). The time-series data was extracted from the NetCDF file using "R." The DUSMASS25 spatial distribution in the 500-km radius area was represented in 357 cells (Annex Map B.1).

Annex Map B.1 Extent of the MERRA-2 Grid Data of Focus Area



Source: Map constructed by authors.

Spatial Distribution of DUSMASS25 Data

The data can be presented as a daily distribution or yearly average distribution. The daily data series was extracted and entered in an Excel spreadsheet to calculate the yearly average for each cell. The $PM_{2.5}$ in kg/m^3 was converted to $\mu g/m^3$ to compare yearly data to international standards. The World Health Organization (WHO) guideline stipulates that $PM_{2.5}$ does not exceed **10 $\mu g/m^3$ annual mean and 25 $\mu g/m^3$ 24-hour mean** (WHO, 2006). The Air Quality Guideline (AQG) of 10 $\mu g/m^3$ is recommended by the WHO as the lower end of the range of concentrations over which adverse health effects due to $PM_{2.5}$ exposure have been observed. The WHO introduced three Interim Targets (IT): IT-1, IT-2, and IT-3 indicating the portion of a country's population living in the aeras where **mean annual concentrations** of $PM_{2.5}$ are greater than **35 $\mu g/m^3$, 25 $\mu g/m^3$**, and **15 $\mu g/m^3$ respectively**. Following the WHO guidelines, Uzbekistan's air quality is considered unsafe (Annex Figure B.1).

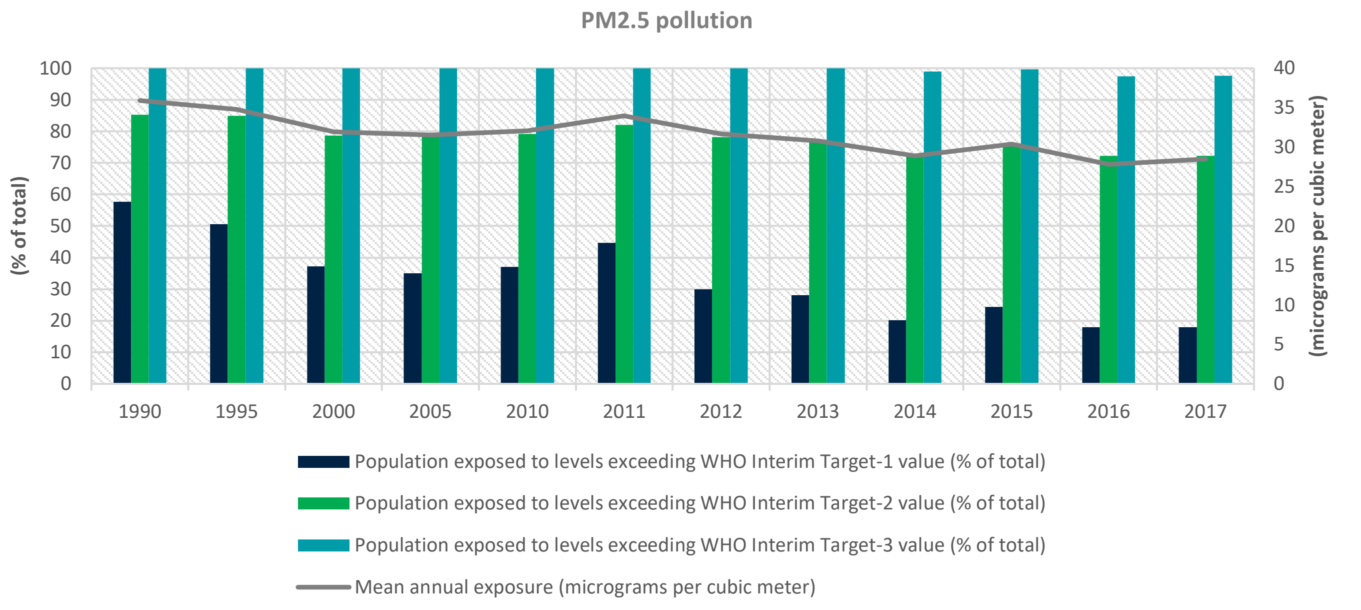
Uzbekistan sanitary guidelines, rules, and standards define maximum allowable concentrations (MAC) of suspended particles in ambient air in accordance with SanPiN №0293-11, dated May 16,2011 (SanPiN, 2011). The MAC list includes single maximum, daily, monthly, and annual levels allowed for different types of dust (Annex Table B.1).

Annex Table B.1 Air Quality Guidelines and Standards

Substance	Maximum Allowable Concentration, µg/m3			
	Event	Day	Month	Year
Uzbekistan (SanPiN, 2011)				
Particulate matter ≤10 µm (PM_{10})	500	300	100	50
Suspended particulates/aerosol	500	350	200	150
Salt dust from Aral	500	300	200	150
Russia (Rospotrebnadzor, 2018)				
Suspended particulates/aerosol	500	150		
Particulate matter ≤10 µm (PM_{10})	300	60		40
Particulate matter ≤2.5 µm ($PM_{2.5}$)	160	35		25
Global (WHO, 2006)				
Particulate matter ≤2.5 µm ($PM_{2.5}$)		25		10
$PM_{2.5}$ Interim target-1 (IT-1)		37.5		15
$PM_{2.5}$ Interim target-2 (IT-2)		50		25
$PM_{2.5}$ Interim target-3 (IT-3)		75		35
Particulate matter ≤10 µm (PM_{10})		50		20
PM_{10} Interim target-1 (IT-1)		75		30
PM_{10} Interim target-2 (IT-2)		100		50
PM_{10} Interim target-3 (IT-3)		150		70

Source: Authors' estimates.

Annex Figure B.1 $PM_{2.5}$ Dynamics in Uzbekistan, 1990-2017

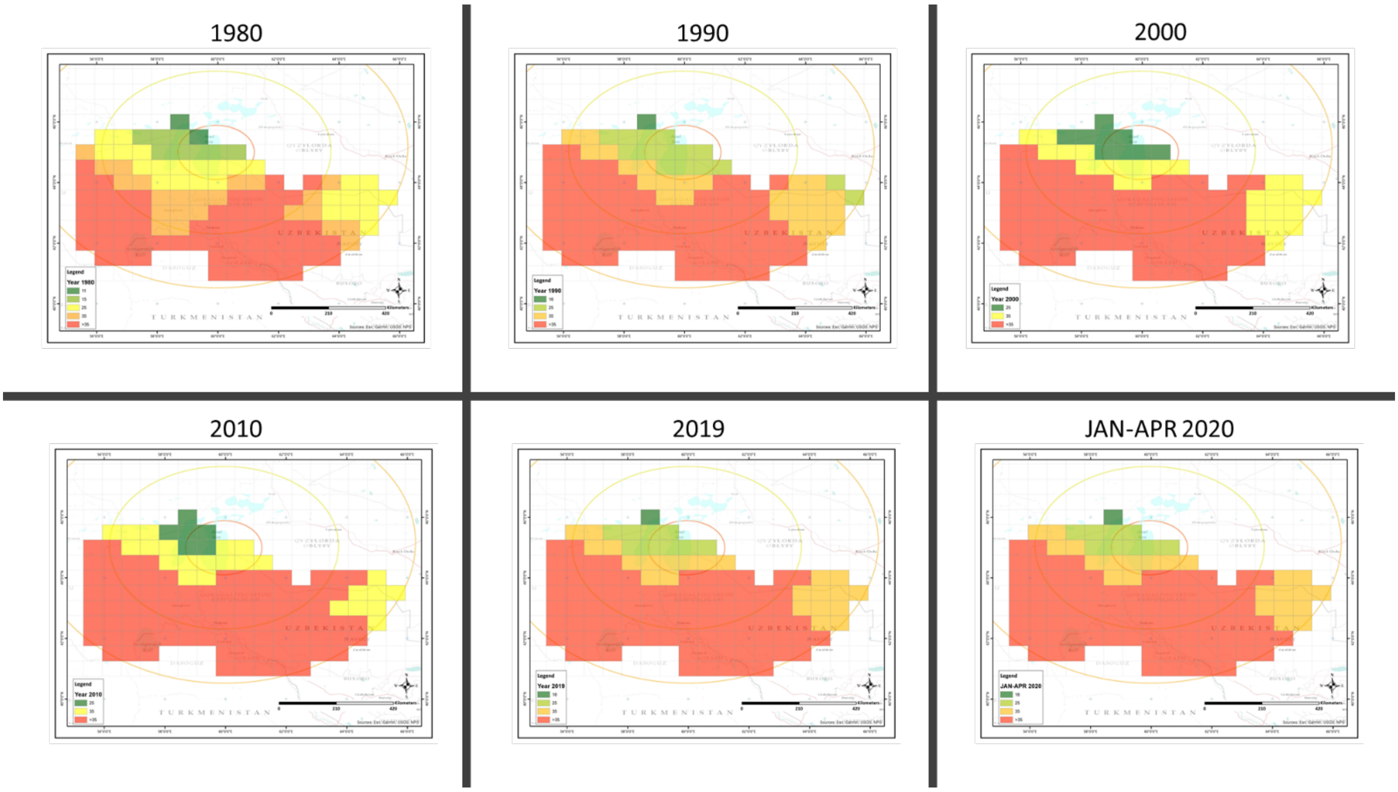


Source: World Bank, World Bank Development Indicators, 2020.

Contributors to poor air quality in Uzbekistan include SDS, waste burning; the mining, oil, and gas industries; and vehicle emissions (IAMAT, 2020).

The average yearly spatial distribution of $PM_{2.5}$ in Uzbekistan can vary yearly. To present the yearly data, a 50-km buffer zone was created around Uzbekistan to extract the country's average yearly data. A total of 120 cell data are presented below for: 1980, 1990, 2000, 2010, 2019, and Jan–Apr 2020 (Annex Map B.2).

Annex Map B.2 Average Yearly Value of $PM_{2.5}$ for 1980, 1990, 2000, 2010, 2019, and Jan–Apr 2020

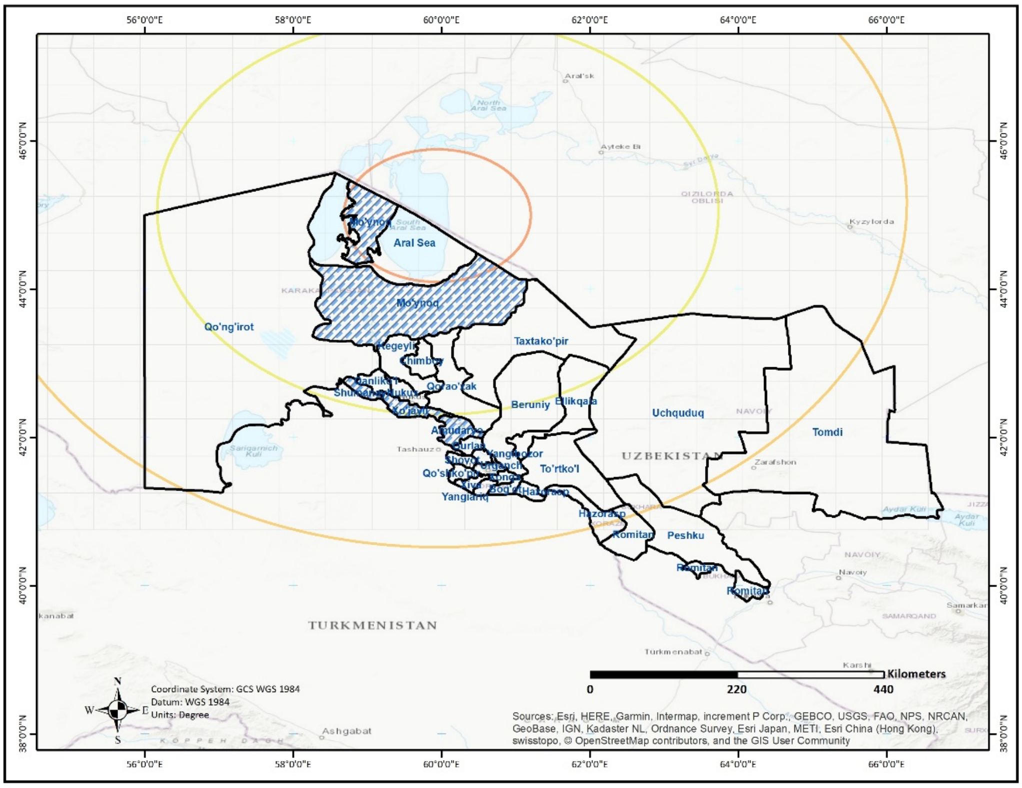


Source: Authors' estimates based on https://disc.gsfc.nasa.gov/.

Time Series Data

The daily health data from the Uzbekistan Health Ministry is available for four districts highlighted in blue in Annex Map B.3 in Karakalpakstan. The cells' data of DUSMASS25 is extracted for most populated areas within the districts (Annex Table B.2). The closest population location is Qubla Usturt (Ka Sjem), located in Qo'ng'irot district located south of the Aral Sea's west shoreline. The largest town is Moynaq, with a population of 13,524 located in the south of the Aral Sea.

Annex Map B.3 Selected Districts for Daily Time Series Data Extraction



Source: Map constructed by authors.

Annex Table B.2 Area and Population Information of Focus Districts in Karakalpakstan and How They Match Observation Grid Cells with $PM_{2.5}$ Data

District	Area (ha)	Population Information	Cell Code with $PM_{2.5}$ Data
Amudaryo	142,508.60	In total, 81 population settlements were identified. Data is available for five locations with a total population of 61,072. The main population areas are: Qipshaq 3,007 Qarataw 3,021 Mang'it 9,200 Qilichboy 5,208 Ayaqchi 636 Located in 300–500 km buffer zone from the Aral Sea center	V81 V97 V98

District	Area (ha)	Population Information	Cell Code with $PM_{2.5}$ Data
Moynaq	2461540.80	In total, 11 population settlements were identified. Data is available for six locations with a total population of 18,648. The main population areas are: Shag'irliq 1,289 Moynaq 13,524 Shege 1,772 Tiko'zek 400 Uchsay 732 Qipshaqdaryo 931 Located in the 100–300 km buffer zone from the Aral Sea center	V31 V46 V47
Shomanay	62447.44	In total, 31 population gatherings were identified. Data is available for one location with a total population of 22400. The main population area is: Shomanay 22,400 Located in the 300–500 km buffer zone from the Aral Sea center	V63 V79 V80
Xo'jayli	133411.35	In total, 46 population gatherings were identified. Data is available for four locations with a total population of (128,507). The main population areas are: Nayman 2,229 Taqıyatas 49,475 Vodnik 5,976 Xo'jayli 70,827 Located in the 300–500 km buffer zone from the Aral Sea center	V79* V80*

Source: Authors compilation.
Note: Data represent two districts.

Review of reports and experiments with documented effect of dust on crop production was analyzed. The following Annex Table B.3 provides a summary of yield penalties on different crops.

Annex Table B.3 Effects of Dust on Crop Production

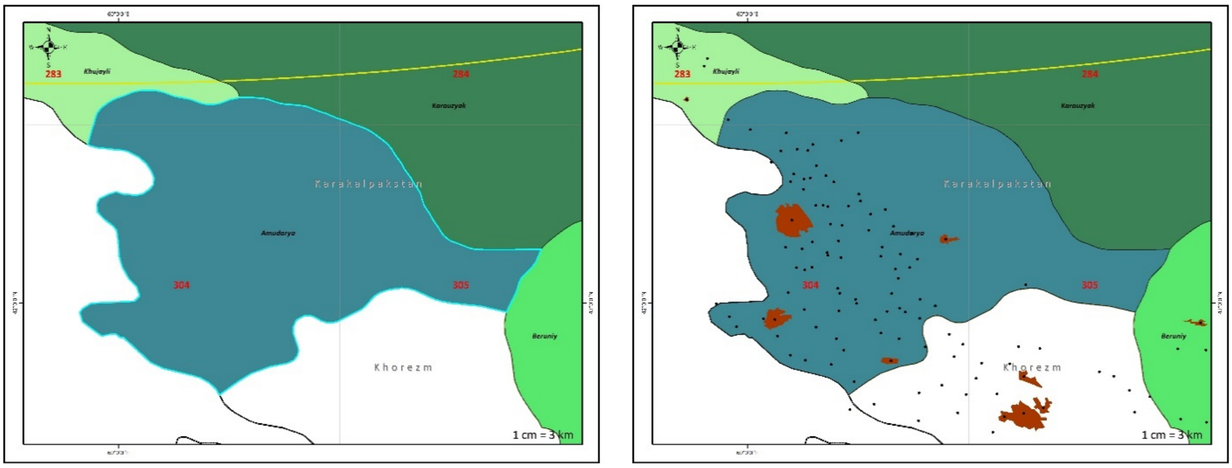
Impact on Crop Yield, %	Crop	Country	Reference
-5-30	Rice, Winter Wheat	China	(Chameides, et al., 1999)
-10	Maize	India, USA	(Greenwald, et al., 2006)
±5	Wheat	India, USA	
±10	Rice	India, Thailand, USA	
-10 (not significant)	Winter wheat	China	(Liu, et al., 2016)
-28%	Cotton	China	(Zia-Khan, et al., 2015)
-30%	Alfalfa	Iran	(Naseri & Ahmady-Birgani, 2019)

Source: Authors' compilation.

Annex C: Extracting and Estimating $PM_{2.5}$ Average per District for 2019 in Karakalpakstan

Average $PM_{2.5}$ values for 2019 were calculated based on available daily values and are presented with spatial distribution of $PM_{2.5}$ cells over each district in Annex Maps C.1-15. Populated places (black dots) and population gatherings (polygons) were examined to verify the cell/s representing the district. Inside each cell, the district area percentages were calculated and presented in tables that follow the district spatial map.

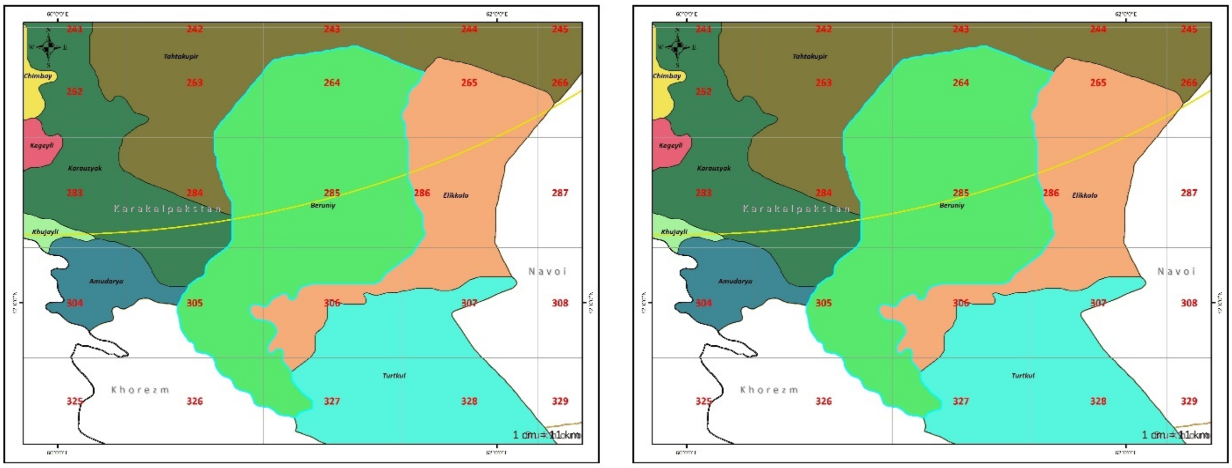
Annex Map C.1 Amudaryo District and $PM_{2.5}$ Cells



Source: Map constructed by authors.

$PM_{2.5}$—Cell Number	Percentage Occupied by District (%)	$PM_{2.5}$ Average in 2019 ($\mu g/m^3$)
304	33.23	60.34
305	11.98	67.21
283	3.73	64.66
284	0.03	74.83

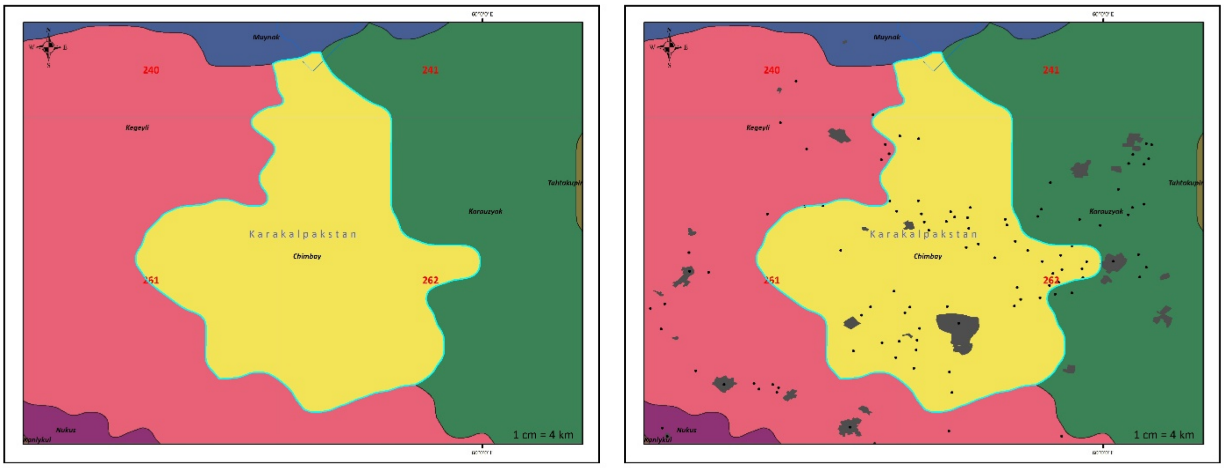
Annex Map C.2 Beruniy District and $PM_{2.5}$ Cells



Source: Map constructed by authors.

$PM_{2.5}$—Cell Number	Percentage Occupied by District (%)	$PM_{2.5}$ Average in 2019 (μg/m^3)
285	100.00	85.00
264	75.69	80.12
305	50.07	67.21
306	36.90	80.18
284	28.21	74.83
327	12.40	80.71
263	11.80	69.11
326	9.65	69.14
286	9.62	71.87
265	3.99	71.61
307	0.83	75.04

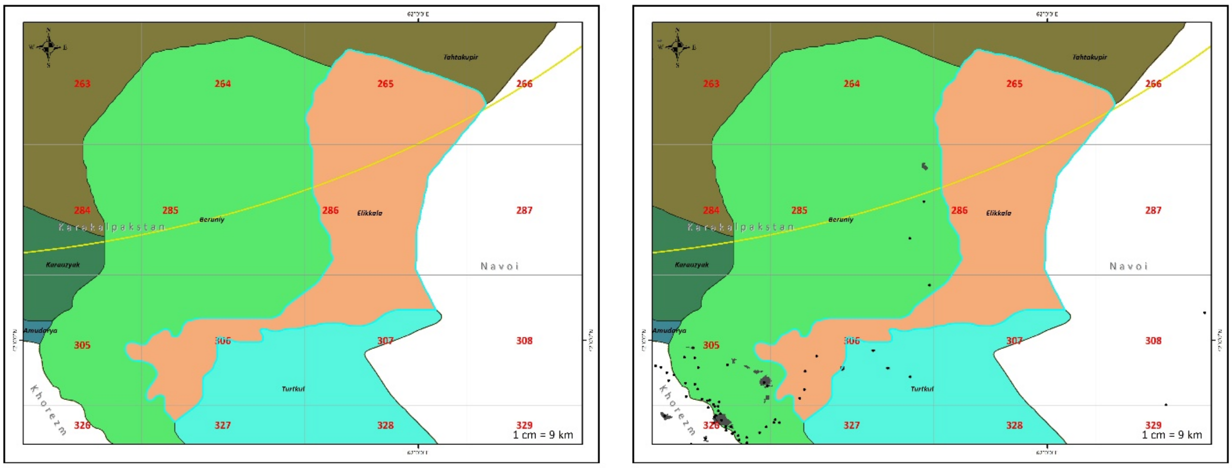
Annex Map C.3 Chimbay District and $PM_{2.5}$ Cells



Source: Map constructed by authors.

$PM_{2.5}$—Cell Number	Percentage Occupied by District (%)	$PM_{2.5}$ Average in 2019 (μg/m^3)
262	30.09	56.71
261	14.65	49.37
241	3.29	49.44
240	0.22	45.67

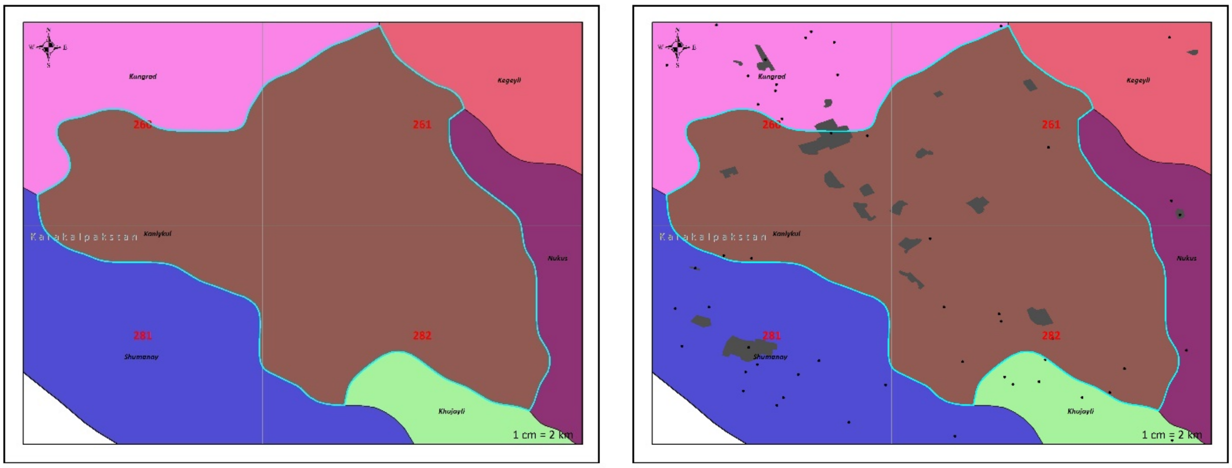
Annex Map C.4 Elikkala District and $PM_{2.5}$ Cells



Source: Map constructed by authors.

$PM_{2.5}$—Cell Number	Percentage Occupied by District (%)	$PM_{2.5}$ Average in 2019 (μg/m³)
286	64.42	71.87
265	56.75	71.61
306	31.63	80.18
307	24.56	75.04
266	2.23	53.42
327	1.35	80.71
305	1.21	67.21

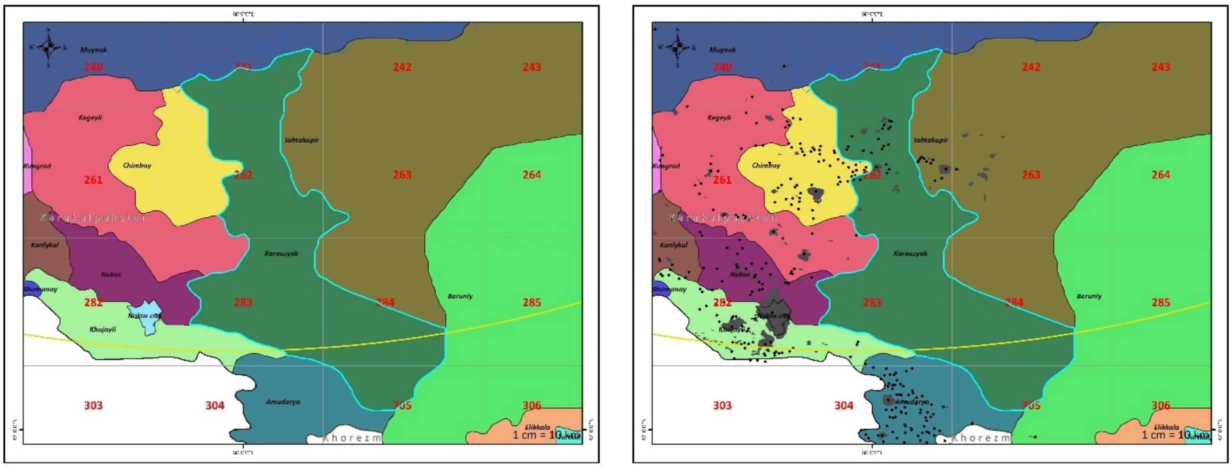
Annex Map C.5 Kanlykul District and $PM_{2.5}$ Cells



Source: Map constructed by authors.

$PM_{2.5}$—Cell Number	Percentage Occupied by District (%)	$PM_{2.5}$ Average in 2019 (μg/m³)
282	11.91	55.28
261	9.44	49.37
260	6.05	46.83
281	2.64	50.21

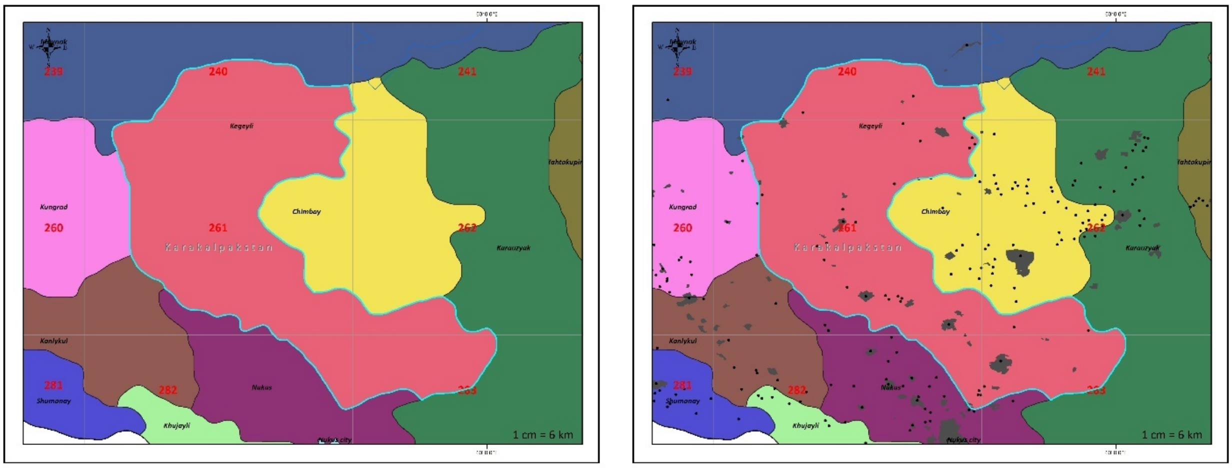
Annex Map C.6 Karauzyak District and $PM_{2.5}$ Cells



Source: Map constructed by authors.

$PM_{2.5}$—Cell Number	Percentage Occupied by District (%)	$PM_{2.5}$ Average in 2019 (μg/m³)
283	56.42	64.66
262	48.83	56.71
284	36.56	74.83
241	22.07	49.44
305	14.72	67.21
263	2.28	69.11

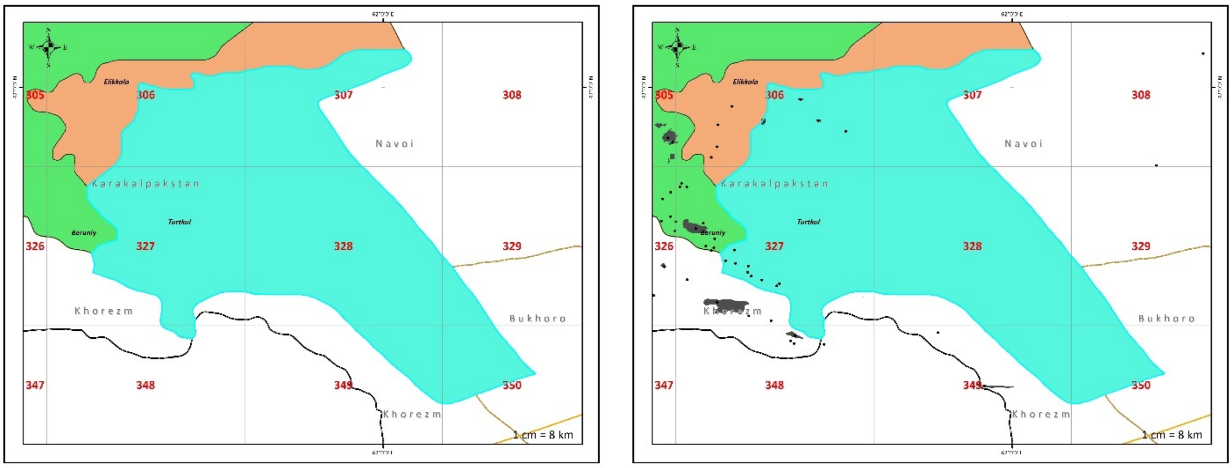
Annex Map C.7 Kegeyli District and $PM_{2.5}$ Cells



Source: Map constructed by authors.

$PM_{2.5}$—Cell Number	Percentage Occupied by District (%)	$PM_{2.5}$ Average in 2019 (μg/m³)
261	61.98	49.37
240	15.67	45.67
283	13.70	64.66
262	5.83	56.71
282	4.79	55.28
241	0.03	49.44

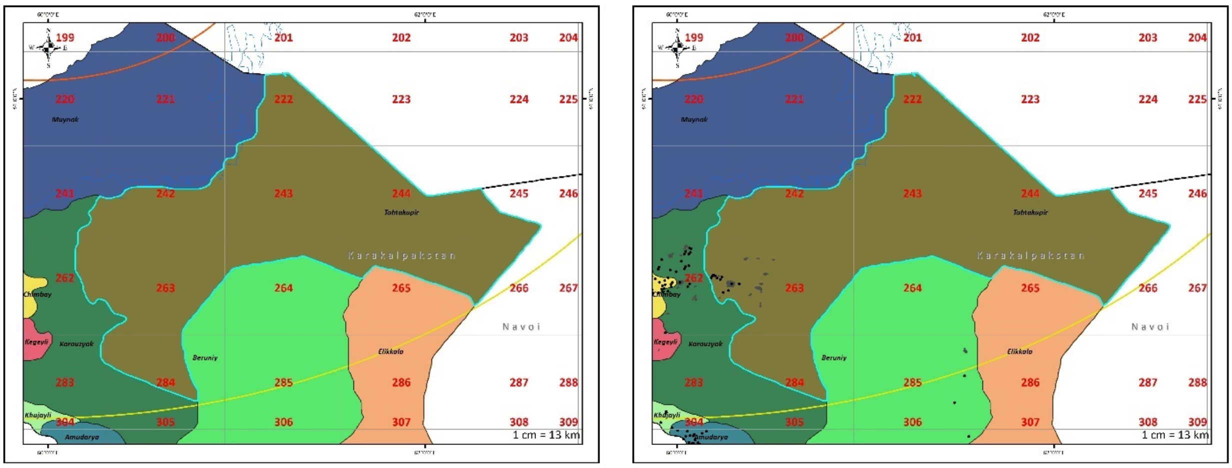
Annex Map C.8 Turtkul District and $PM_{2.5}$ Cells



Source: Map constructed by authors.

$PM_{2.5}$—Cell Number	Percentage Occupied by District (%)	$PM_{2.5}$ Average in 2019 (μg/m^3)
328	80.28	80.39
327	61.02	80.71
307	35.34	75.04
306	31.46	80.18
350	15.63	74.37
349	12.19	81.83
329	5.86	72.90
348	0.93	83.59

Annex Map C.9 Tahtakupir District and $PM_{2.5}$ Cells

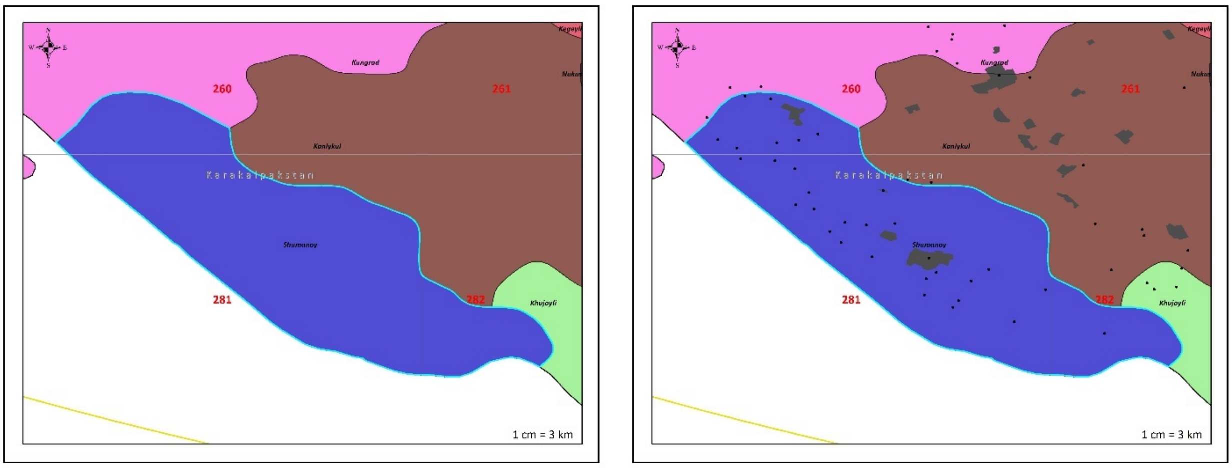


Source: Map constructed by authors

$PM_{2.5}$—Cell Number	Percentage Occupied by District (%)	$PM_{2.5}$ Average in 2019 (μg/m^3)
243	98.80	68.45
263	85.92	69.11
244	72.85	68.88
242	56.39	59.27

$PM_{2.5}$—Cell Number	Percentage Occupied by District (%)	$PM_{2.5}$ Average in 2019 ($\mu g/m^3$)
222	43.51	52.90
265	38.74	71.61
284	35.19	74.83
264	24.31	80.12
266	24.20	53.42
245	23.69	54.72
262	15.25	56.71
241	7.51	49.44
223	3.18	55.34
283	1.33	64.66

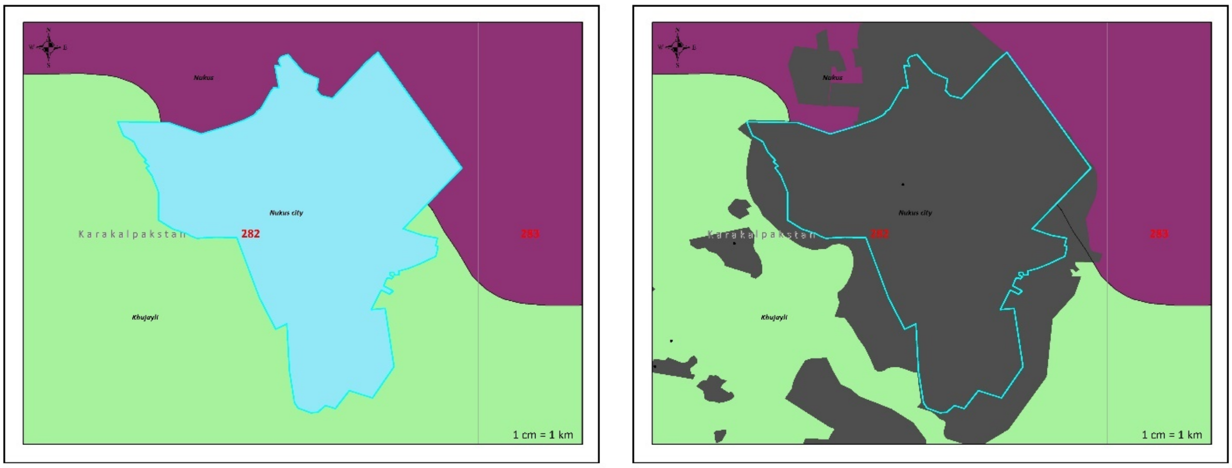
Annex Map C.10 Shumanay District and $PM_{2.5}$ Cells



Source: Map constructed by authors.

$PM_{2.5}$—Cell Number	Percentage Occupied by District (%)	$PM_{2.5}$ Average in 2019 ($\mu g/m^3$)
281	15.33	50.21
282	3.12	55.28
260	3.10	46.83

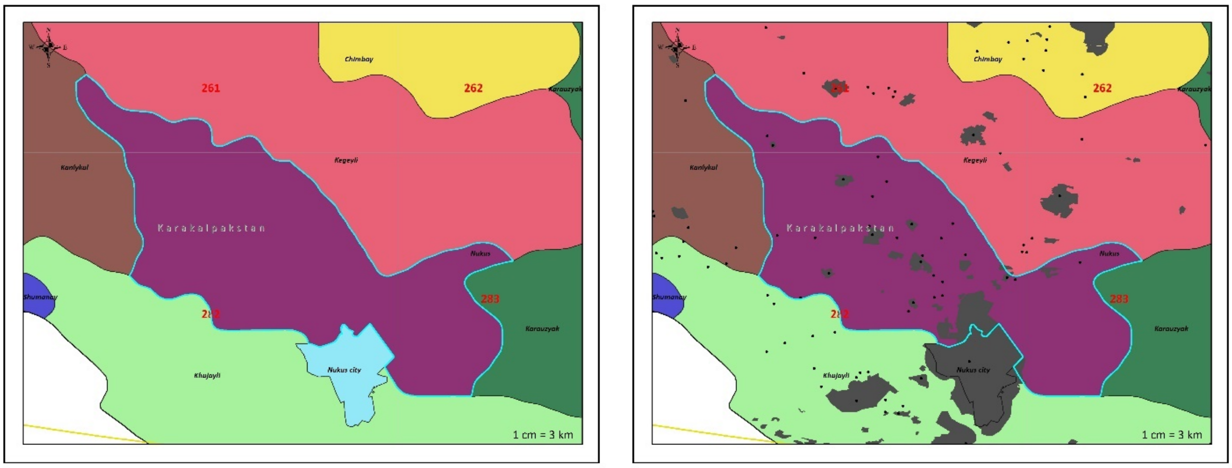
Annex Map C.11 Nukus City District and $PM_{2.5}$ Cells



Source: Map constructed by authors.

$PM_{2.5}$—Cell Number	Percentage Occupied by District (%)	$PM_{2.5}$ Average in 2019 ($\mu g/m^3$)
282	3.08	55.28

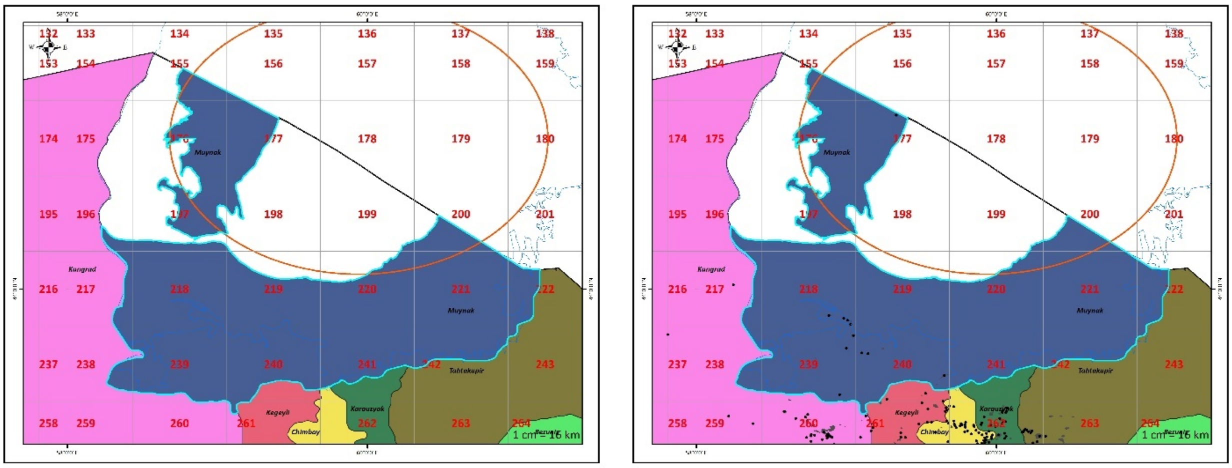
Annex Map C.12 Nukus District and $PM_{2.5}$ Cells



Source: Map constructed by authors.

$PM_{2.5}$—Cell Number	Percentage Occupied by District (%)	$PM_{2.5}$ Average in 2019 ($\mu g/m^3$)
282	23.50	55.28
283	7.88	64.66
261	3.46	49.37
282	0.00	55.28

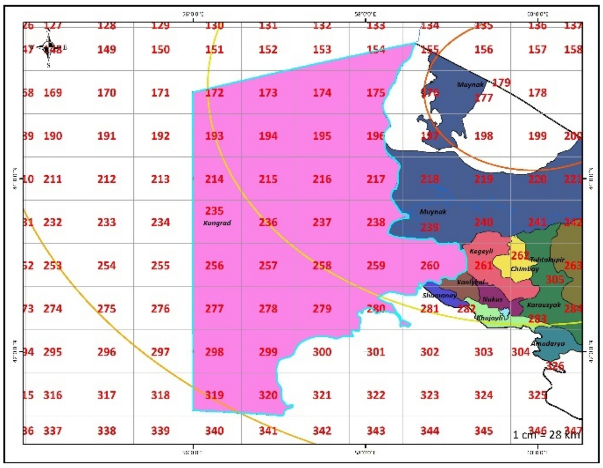
Annex Map C.13 Moynaq District and $PM_{2.5}$ Cells

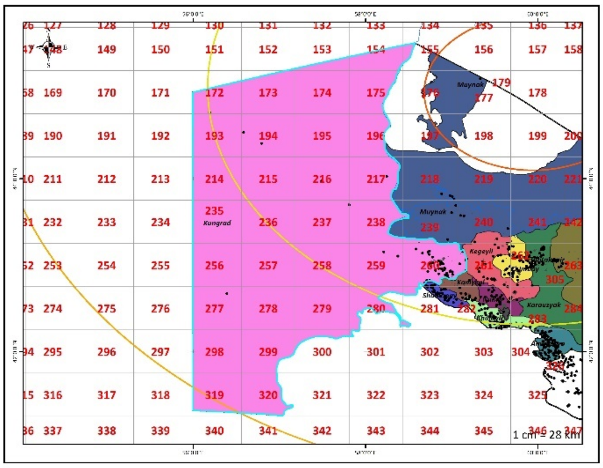


Source: Map constructed by authors.

$PM_{2.5}$—Cell Number	Percentage Occupied by District (%)	$PM_{2.5}$ Average in 2019 ($\mu g/m^3$)
218	100.00	37.84
221	99.36	44.35
239	92.32	43.52
240	84.11	45.67
220	75.00	40.17
219	71.63	38.04
241	67.10	49.44
197	49.75	31.56
176	47.49	27.06
242	43.61	59.27
177	39.58	27.19
222	22.83	52.90
200	21.20	33.84
155	15.10	23.57
217	12.86	44.89
238	12.63	52.40
198	6.65	32.27
196	5.51	35.71
199	1.45	32.99
156	1.30	23.31
261	1.28	49.37
243	1.20	68.45
260	0.12	46.83

Annex Map C.14 Kungrad District and $PM_{2.5}$ Cells



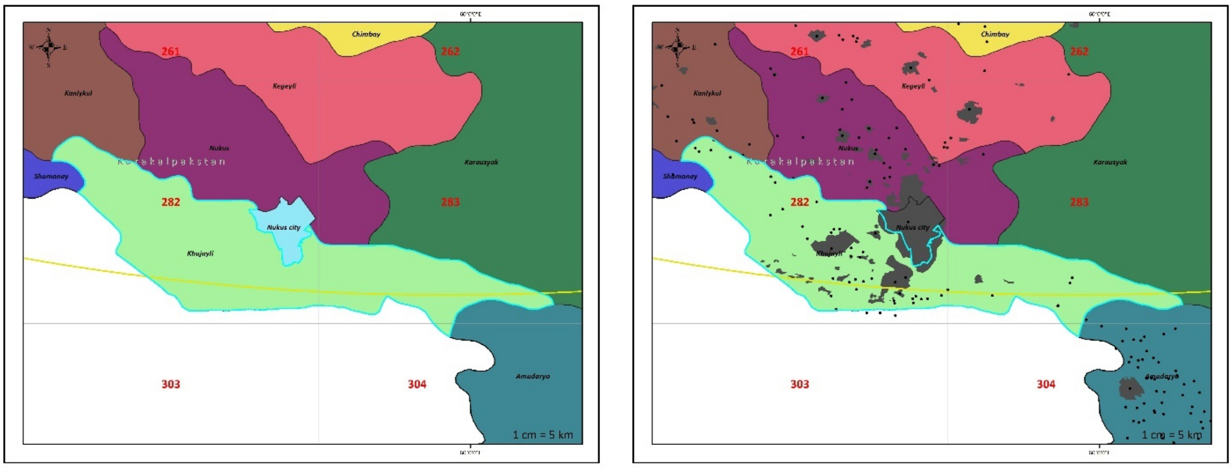


Source: Map constructed by authors.

$PM_{2.5}$—Cell Number	Percentage Occupied by District (%)	$PM_{2.5}$ Average in 2019 (μg/m^3)
174	100.00	30.24
194	100.00	44.52
195	100.00	41.71
215	100.00	57.89
216	100.00	53.98
236	100.00	65.34
237	100.00	60.54
257	100.00	63.56
258	100.00	59.36
259	100.00	50.58
278	100.00	72.03
279	100.00	59.79
173	90.42	34.28
260	90.29	46.83
193	90.27	47.14
214	90.21	58.79
235	90.16	64.24
256	90.10	68.02
277	90.04	74.45
298	89.95	72.64
299	87.62	72.20
238	87.37	52.40
217	87.14	44.89
319	79.84	65.60
175	74.36	27.81
320	70.94	64.06
196	69.24	35.71
172	57.12	38.81
280	53.54	51.41
154	44.93	24.10
300	19.61	65.74

$PM_{2.5}$—Cell Number	Percentage Occupied by District (%)	$PM_{2.5}$ Average in 2019 ($\mu g/m^3$)
153	18.78	25.83
261	9.18	49.37
239	7.68	43.52
281	6.38	50.21
155	6.22	23.57
301	1.03	58.69
152	0.46	28.23
240	0.00	45.67

Annex Map C.15 Khujayli District and $PM_{2.5}$ Cells



Source:

$PM_{2.5}$—Cell Number	Percentage Occupied by District (%)	$PM_{2.5}$ Average in 2019 ($\mu g/m^3$)
282	29.92	55.28
283	14.54	64.66
304	0.20	60.34
282	0.00	55.28

District areas that present/occupy 10% of the $PM_{2.5}$ cell area were considered, especially for large area districts. Only in the following cases, the cell value was considered as many population points exist and/or population gathering (polygons).

(i) For Beruniy district the value of cell 362.

(ii) For Kanlykul district, the values of cells 282, 261, and 260.

(iii) For Kungrad district, the value of cell 261.

(iv) For Nukus district, the value of cells 283 and 261.

(v) For Nukus city the value of cell 282 due to the small extent of the city location and large population.

(vi) For Shumanay district, the values of cells 282 and 260.

Annex C: Table 1 Average $PM_{2.5}$ Values by District

District	$PM_{2.5}$—Cell Number	Percentage Occupied by District (%)	$PM_{2.5}$ Average in 2019 (μg/m³)
Amudaryo	304	33.23	60.34
Amudaryo	305	11.98	67.21
Amudaryo	283	3.73	64.66
Amudaryo	284	0.03	74.83
Beruniy	285	100.00	85.00
Beruniy	264	75.69	80.12
Beruniy	305	50.07	67.21
Beruniy	306	36.90	80.18
Beruniy	284	28.21	74.83
Beruniy	327	12.40	80.71
Beruniy	263	11.80	69.11
Beruniy	326	9.65	69.14
Beruniy	286	9.62	71.87
Beruniy	265	3.99	71.61
Beruniy	307	0.83	75.04
Chimbay	262	30.09	56.71
Chimbay	261	14.65	49.37
Chimbay	241	3.29	49.44
Chimbay	240	0.22	45.67
Elikkala	286	64.42	71.87
Elikkala	265	56.75	71.61
Elikkala	306	31.63	80.18
Elikkala	307	24.56	75.04
Elikkala	266	2.23	53.42
Elikkala	327	1.35	80.71
Elikkala	305	1.21	67.21
Kanlykul	282	11.91	55.28
Kanlykul	261	9.44	49.37
Kanlykul	260	6.05	46.83
Kanlykul	281	2.64	50.21
Karauzyak	283	56.42	64.66
Karauzyak	262	48.83	56.71
Karauzyak	284	36.56	74.83
Karauzyak	241	22.07	49.44
Karauzyak	305	14.72	67.21
Karauzyak	263	2.28	69.11
Kegeyli	261	61.98	49.37
Kegeyli	240	15.67	45.67
Kegeyli	283	13.70	64.66
Kegeyli	262	5.83	56.71
Kegeyli	282	4.79	55.28
Kegeyli	241	0.03	49.44
Khujayli	282	29.92	55.28
Khujayli	283	14.54	64.66

District	$PM_{2.5}$—Cell Number	Percentage Occupied by District (%)	$PM_{2.5}$ Average in 2019 (μg/m³)
Khujayli	304	0.20	60.34
Khujayli	282	0.00	55.28
Kungrad	174	100.00	30.24
Kungrad	194	100.00	44.52
Kungrad	195	100.00	41.71
Kungrad	215	100.00	57.89
Kungrad	216	100.00	53.98
Kungrad	236	100.00	65.34
Kungrad	237	100.00	60.54
Kungrad	257	100.00	63.56
Kungrad	258	100.00	59.36
Kungrad	259	100.00	50.58
Kungrad	278	100.00	72.03
Kungrad	279	100.00	59.79
Kungrad	173	90.42	34.28
Kungrad	260	90.29	46.83
Kungrad	193	90.27	47.14
Kungrad	214	90.21	58.79
Kungrad	235	90.16	64.24
Kungrad	256	90.10	68.02
Kungrad	277	90.04	74.45
Kungrad	298	89.95	72.64
Kungrad	299	87.62	72.20
Kungrad	238	87.37	52.40
Kungrad	217	87.14	44.89
Kungrad	319	79.84	65.60
Kungrad	175	74.36	27.81
Kungrad	320	70.94	64.06
Kungrad	196	69.24	35.71
Kungrad	172	57.12	38.81
Kungrad	280	53.54	51.41
Kungrad	154	44.93	24.10
Kungrad	300	19.61	65.74
Kungrad	153	18.78	25.83
Kungrad	261	9.18	49.37
Kungrad	239	7.68	43.52
Kungrad	281	6.38	50.21
Kungrad	155	6.22	23.57
Kungrad	301	1.03	58.69
Kungrad	152	0.46	28.23
Kungrad	240	0.00	45.67
Moynaq	218	100.00	37.84
Moynaq	221	99.36	44.35
Moynaq	239	92.32	43.52
Moynaq	240	84.11	45.67
Moynaq	220	75.00	40.17
Moynaq	219	71.63	38.04
Moynaq	241	67.10	49.44
Moynaq	197	49.75	31.56
Moynaq	176	47.49	27.06
Moynaq	242	43.61	59.27
Moynaq	177	39.58	27.19

District	$PM_{2.5}$—Cell Number	Percentage Occupied by District (%)	$PM_{2.5}$ Average in 2019 (µg/m³)
Moynaq	222	22.83	52.90
Moynaq	200	21.20	33.84
Moynaq	155	15.10	23.57
Moynaq	217	12.86	44.89
Moynaq	238	12.63	52.40
Moynaq	198	6.65	32.27
Moynaq	196	5.51	35.71
Moynaq	199	1.45	32.99
Moynaq	156	1.30	23.31
Moynaq	261	1.28	49.37
Moynaq	243	1.20	68.45
Moynaq	260	0.12	46.83
Nukus	282	23.50	55.28
Nukus	283	7.88	64.66
Nukus	261	3.46	49.37
Nukus	282	0.00	55.28
Nukus city	282	3.08	55.28
Shumanay	281	15.33	50.21
Shumanay	282	3.12	55.28
Shumanay	260	3.10	46.83
Tahtakupir	243	98.80	68.45
Tahtakupir	263	85.92	69.11
Tahtakupir	244	72.85	68.88
Tahtakupir	242	56.39	59.27
Tahtakupir	222	43.51	52.90
Tahtakupir	265	38.74	71.61
Tahtakupir	284	35.19	74.83
Tahtakupir	264	24.31	80.12
Tahtakupir	266	24.20	53.42
Tahtakupir	245	23.69	54.72
Tahtakupir	262	15.25	56.71
Tahtakupir	241	7.51	49.44
Tahtakupir	223	3.18	55.34
Tahtakupir	283	1.33	64.66
Turtkul	328	80.28	80.39
Turtkul	327	61.02	80.71
Turtkul	307	35.34	75.04
Turtkul	306	31.46	80.18
Turtkul	350	15.63	74.37
Turtkul	349	12.19	81.83
Turtkul	329	5.86	72.90
Turtkul	348	0.93	83.59

Source: Authors' compilation.
Note: Values in light grey are the ones excluded from the average.

Annex D: On-Site Impacts: Quantification and Valuation of Ecosystem Services, Crop Yields, and Human Lives Lost Due to Inaction

Annex Table D.1 Lower Bound: Carbon from Biomass, t/ha (Above Ground) with Assumed Total Success Rate of 49.5% (15.69% for the First Planting with 1.57% Natural Succession, 15.69% for the Second Replanting with 3.16% Natural Succession, and 15.69% for the Third Replanting with 4.78% Natural Succession)

		Estimates of Quantities of Ecosystem Services				Quantities and Values of the Ecosystem Services Lost Due to Inaction to Fully Restore the Aralkum Desert with Trees and Grass Cover (Scenario 4)		
Item	Increase Per Year	Scenario 1 (Current Scenario) 90% Bare (-) and 10% Bare (+)	Scenario 2 50% Shrub (-) and 50% Shrub (+)	Scenario 3 50% Tree (-) and 50% Tree (+)	Scenario 4 (Best Possible Scenario) 100% Tree (+)	Scenario 1 (Current Scenario) 90% Bare (-) and 10% Bare (+)	Scenario 2 50% Shrub (-) and 50% Shrub (+)	Scenario 3 50% Tree (-) and 50% Tree (+)
Parameter values per unit area	Carbon from biomass, t/ha (above ground) with assumed total success rate of 89% (30% with first planting, 50% with second replanting and 70% with third replanting)	0.01	0.45	0.76	1.04	(1.04)	(0.60)	(0.28)
	Carbon from biomass, t/ha (below ground) with assumed total success rate of 89% (30% with first planting, 50% with second replanting and 70% with third replanting)	0.01	0.58	1.04	1.42	(1.41)	(0.84)	(0.38)
	Soil carbon, t/ha	23.26	23.61	23.79	24.32	(1.06)	(0.71)	(0.53)
	Biodiversity, index							
Quantities of ecosystem services	Carbon from above ground biomass (tonnes)	12,554	588,488	1,004,353	1,380,985	(1,368,430.85)	(792,497.22)	(376,632.34)
	Carbon from below ground biomass (tonnes)	16,792	765,819	1,377,062	1,875,315	(1,858,523.68)	(1,109,496.11)	(498,253.20)
	Soil carbon (tonnes)	30,752,046	31,219,567	31,454,962	32,157,879	(1,405,832.53)	(938,311.48)	(702,916.27)
Values of ecosystem services under different scenarios[18]	Total value of carbon from above-ground biomass ($)	460,328	31,456,232	53,837,471	74,107,272	(73,646,943.69)	(42,651,039.64)	(20,269,801.02)
	Total value of carbon from below-ground biomass ($)	615,689	40,927,256	73,823,454	100,638,712	(100,023,022.26)	(59,711,455.49)	(26,815,257.59)
	Total value of soil carbon ($)	1,127,575,020	1,175,149,595	1,199,904,844	1,269,021,181	(141,446,161.25)	(93,871,585.90)	(69,116,337.74)
	Total value of grazing or forage that can be harvested ($)		27,605,380	54,790,219	75,879,073	(75,879,073.41)	(48,273,693.58)	(21,088,854.61)
	Value of firewood that can be harvested ($)		-	39,768,027	96,686,118	(96,686,117.83)	(96,686,117.83)	(56,918,091.19)
Total values of ecosystem services after the 20th year		**1,128,651,038**	**1,275,138,464**	**1,422,124,014**	**1,616,332,356**	**(487,681,318)**	**(341,193,892)**	**(194,208,342)**
Average annual value of ecosystem services lost due to inaction to fully restore the Aralkum Desert with trees and grass cover ($) (assuming 20 years of loss)		(24,384,066)	(17,059,695)	(9,710,417)				
% gain (+) or loss (-) lost due to inaction		-30.17%	-21.11%	-12.02%	0.00%			
Gain (+) or loss (-) as equivalent to % of Karakalpakstan's GDP		-1.15%	-0.81%	-0.46%	0.00%			
Cost of action: First planting + first replanting + second replanting: assuming 50% and 25% of original cost for the first and second replanting, respectively ($)		NA	462,082,634	462,082,634	462,082,634			
Annualized benefit: Cost ratio (assuming 20-year planning period)			0.32	0.64	1.06			

Source: Authors' estimates.

[18] A CO_2 price of $10/tonne is used and converted to carbon price as follows: (44/12)*$10 = $36.67/tonne (World Bank, 2019).

Annex Table D.2 Average: Carbon from Biomass, t/ha (Above Ground) with Assumed Total Success Rate of 72.3% (25.07% for the First Planting with 2.51% Natural Succession, 25.07% for the Second Replanting with 5.08% Natural Succession, and 25.07% for the Third Replanting with 7.71% Natural Succession)

		Estimates of Quantities of Ecosystem Services				Quantities and Values of the Ecosystem Services Lost Due to Inaction to Fully Restore the Aralkum Desert with Trees and Grass Cover (Scenario 4)		
Item	**Increase Per Year**	**Scenario 1 (Current Scenario) 90% Bare (-) and 10% Bare (+)**	**Scenario 2 50% Shrub (-) and 50% Shrub (+)**	**Scenario 3 50% Tree (-) and 50% Tree (+)**	**Scenario 4 (Best Possible Scenario) 100% Tree (+)**	**Scenario 1 (Current Scenario) 90% Bare (-) and 10% Bare (+)**	**Scenario 2 50% Shrub (-) and 50% Shrub (+)**	**Scenario 3 50% Tree (-) and 50% Tree (+)**
Parameter values per unit area	Carbon from biomass, t/ha (above ground) with assumed total success rate of 89% (30% with first planting, 50% with second replanting and 70% with third replanting)	0.01	0.65	1.11	1.53	(1.51)	(0.88)	(0.42)
	Carbon from biomass, t/ha (below ground) with assumed total success rate of 89% (30% with first planting, 50% with second replanting and 70% with third replanting)	0.02	0.85	1.52	2.07	(2.06)	(1.23)	(0.55)
	Soil carbon, t/ha	23.26	23.78	24.04	24.81	(1.55)	(1.04)	(0.78)
	Biodiversity, index							
Quantities of ecosystem services	Carbon from above ground biomass (tonnes)	18,355	860,408	1,468,430	2,019,092	(2,000,736.40)	(1,158,683.35)	(550,661.40)
	Carbon from below ground biomass (tonnes)	24,550	1,119,678	2,013,356	2,741,835	(2,717,284.54)	(1,622,156.69)	(728,479.14)
	Soil carbon (tonnes)	30,752,046	31,435,593	31,779,756	32,807,466	(2,055,420.14)	(1,371,873.44)	(1,027,710.07)
Values of ecosystem services under different scenarios[19]	Total value of carbon from above-ground biomass ($)	673,031	45,991,092	78,713,943	108,349,733	(107,676,702.43)	(62,358,640.74)	(29,635,789.66)
	Total value of carbon from below-ground biomass ($)	900,178	59,838,355	107,934,772	147,140,452	(146,240,273.72)	(87,302,097.04)	(39,205,680.07)
	Total value of soil carbon ($)	1,127,575,020	1,197,132,196	1,233,326,006	1,334,378,663	(206,803,642.52)	(137,246,466.93)	(101,052,656.90)
	Total value of grazing or forage that can be harvested ($)		40,360,891	80,406,217	110,940,224	(110,940,223.72)	(70,579,332.67)	(30,534,006.53)
	Value of firewood that can be harvested ($)		-	102,454,664	80,223,290	(80,223,289.51)	(80,223,289.51)	22,231,374.72
Total values of ecosystem services after the 20th year		**1,129,148,229**	**1,343,322,534**	**1,602,835,602**	**1,781,032,361**	**(651,884,132)**	**(437,709,827)**	**(178,196,758)**
Average annual value of ecosystem services lost due to inaction to fully restore the Aralkum Desert with trees and grass cover ($) (assuming 20 years of loss)		(32,594,207)	(21,885,491)	(8,909,838)	-	TRUE	TRUE	TRUE
% gain (+) or loss (-) lost due to inaction		-36.60%	-24.58%	-10.01%	0.00%			
Gain (+) or loss (-) as equivalent to % of Karakalpakstan's GDP		-1.54%	-1.04%	-0.42%	0.00%			
Cost of action: First planting + first replanting + second replanting: assuming 50% and 25% of original cost for the first and second replanting, respectively ($)		NA	524,744,105	524,744,105	524,744,105			
Annualized benefit: Cost ratio (assuming 20-year planning period)			0.41	0.90	1.24			

Source: Authors' estimates.

[19] A CO_2 price of $10/tonne is used and converted to a carbon price as follows: (44/12)*$10 = $36.67/tonne (World Bank, 2019).

Annex Table D.3 Upper Bound: Carbon from Biomass, t/ha (Above Ground) with Assumed Total Success Rate of (43.3% for the First Planting with 4.33% Natural Succession and 43.3% for the Second Replanting with 8.85% Natural Succession with No Third Replanting but a High Natural Succession Rate of 9.23%)

		Estimates of Quantities of Ecosystem Services				Quantities and Values of the Ecosystem Services Lost Due to Inaction to Fully Restore the Aralkum Desert with Trees and Grass Cover (Scenario 4)		
Item	**Increase Per Year**	**Scenario 1 (Current Scenario) 90% Bare (-) and 10% Bare (+)**	**Scenario 2 50% Shrub (-) and 50% Shrub (+)**	**Scenario 3 50% Tree (-) and 50% Tree (+)**	**Scenario 4 (Best Possible Scenario) 100% Tree (+)**	**Scenario 1 (Current Scenario) 90% Bare (-) and 10% Bare (+)**	**Scenario 2 50% Shrub (-) and 50% Shrub (+)**	**Scenario 3 50% Tree (-) and 50% Tree (+)**
Parameter values per unit area	Carbon from biomass, t/ha (above ground) with assumed total success rate of 89% (30% with first planting, 50% with second replanting and 70% with third replanting)	0.02	0.71	1.22	1.68	(1.66)	(0.96)	(0.46)
	Carbon from biomass, t/ha (below ground) with assumed total success rate of 89% (30% with first planting, 50% with second replanting and 70% with third replanting)	0.03	0.93	1.67	2.28	(2.25)	(1.35)	(0.60)
	Soil carbon, t/ha	23.26	23.83	24.11	24.97	(1.71)	(1.14)	(0.85)
	Biodiversity, index							
Quantities of ecosystem services	Carbon from above ground biomass (tonnes)	25,384	944,311	1,611,625	2,215,984	(2,190,599.47)	(1,271,672.51)	(604,359.21)
	Carbon from below ground biomass (tonnes)	33,952	1,228,864	2,209,688	3,009,205	(2,975,253.73)	(1,780,341.52)	(799,516.88)
	Soil carbon (tonnes)	30,752,046	31,502,249	31,879,973	33,007,901	(2,255,854.71)	(1,505,651.86)	(1,127,927.35)
Values of ecosystem services under different scenarios[20]	Total value of carbon from above-ground biomass ($)	930,758	50,386,061	86,299,885	118,825,613	(117,894,854.50)	(68,439,551.95)	(32,525,727.66)
	Total value of carbon from below-ground biomass ($)	1,244,889	65,553,314	118,339,860	161,368,687	(160,123,797.47)	(95,815,372.73)	(43,028,827.22)
	Total value of soil carbon ($)	1,127,575,020	1,176,199,466	1,201,657,428	1,272,675,085	(145,100,065.09)	(96,475,618.69)	(71,017,656.60)
	Total value of grazing or forage that can be harvested ($)		44,045,575	87,956,539	121,468,073	(121,468,072.83)	(77,422,497.98)	(33,511,534.26)
	Value of firewood that can be harvested ($)		-	63,603,287	154,776,223	(154,776,223.19)	(154,776,223.19)	(91,172,936.46)
Total values of ecosystem services after the 20th year			**1,129,148,229**	**1,129,750,668**	**1,336,184,416**	**1,557,856,999**	**1,829,113,681**	**(699,363,013)**
Average annual value of ecosystem services lost due to inaction to fully restore the Aralkum Desert with trees and grass cover ($) (assuming 20 years of loss)		(32,594,207)	(34,968,151)	(24,646,463)	(13,562,834)	-	TRUE	TRUE
% gain (+) or loss (-) lost due to inaction		-36.60%	-38.24%	-26.95%	-14.83%	0.00%		
Gain (+) or loss (-) as equivalent to % of Karakalpakstan's GDP		-1.54%	-1.66%	-1.17%	-0.64%	0.00%		
Cost of action: First planting + first replanting + second replanting: assuming 50% and 25% of original cost for the first and second replanting, respectively ($)		NA	NA	470,413,150	470,413,150	470,413,150		
Annualized benefit: Cost ratio (assuming 20-year planning period)				0.44	0.91	1.49		

Source: Authors' estimates.

[20] A CO_2 price of $ 10/tonne is used and converted to carbon price as follows: (44/12)*$10 = $36.67/tonne (World Bank, 2019)..

Annex Table E.1 Values of Total Production and Estimates of Specific Crop Values Lost Due to Inaction to Restore the Aralkum

District	Value of Total Production Lost Due to SDS from the Aralkum ($)																			
	All Grains				Cotton				Potatoes				Vegetables				Melones and Gourds			
	Value of Total Production ($)	Loss: Lower Bound ($)	Loss: Average ($)	Loss: Upper Bound ($)	Value of Total Production ($)	Loss: Lower Bound ($)	Loss: Average ($)	Loss: Upper Bound ($)	Value of Total Production ($)	Loss: Lower Bound ($)	Loss: Average ($)	Loss: Upper Bound ($)	Value of Total Production ($)	Loss: Lower Bound ($)	Loss: Average ($)	Loss: Upper Bound ($)	Value of Total Production ($)	Loss: Lower Bound ($)	Loss: Average ($)	Loss: Upper Bound ($)
Nukus City	65,848	1,129	2,258	3,386	61,088	1,047	2,094	3,142	125,780	2,156	4,312	6,469	3,354,613	57,508	115,015	172,523	357,662	6,131	12,263	18,394
Amudaryo	18,917,821	50,673	101,345	152,018	17,550,314	47,010	94,020	141,029	5,200,880	13,931	27,862	41,793	44,629,687	119,544	239,088	358,631	9,760,526	26,144	52,289	78,433
Beruniy	8,110,886	21,726	43,451	65,177	7,524,577	20,155	40,310	60,465	2,695,334	7,220	14,439	21,659	19,844,902	53,156	106,312	159,468	8,170,161	21,884	43,769	65,653
Karauzyak	4,412,178	75,637	151,275	226,912	4,093,236	70,170	140,340	210,509	705,768	12,099	24,198	36,297	4,136,244	70,907	141,814	212,721	3,456,411	59,253	118,506	177,758
Kegeyli	4,578,157	78,483	156,965	235,448	4,247,217	72,809	145,619	218,428	501,165	8,591	17,183	25,774	5,907,586	101,273	202,546	303,819	3,592,764	61,590	123,180	184,771
Kungrad	5,907,343	101,269	202,537	303,806	5,480,320	93,948	187,897	281,845	1,109,663	19,023	38,046	57,068	9,042,115	155,008	310,015	465,023	2,080,983	35,674	71,348	107,022
Kanlykul	4,279,463	73,362	146,724	220,087	3,970,115	68,059	136,118	204,177	254,076	4,356	8,711	13,067	4,652,441	79,756	159,512	239,268	2,701,582	46,313	92,626	138,938
Moynaq	467,048	46,705	93,410	140,114	433,287	43,329	86,657	129,986	441,349	44,135	88,270	132,405	2,273,534	227,353	454,707	682,060	480,423	48,042	96,085	144,127
Nukus	5,656,508	141,413	110,479	79,545	5,247,618	131,190	102,493	73,795	895,557	22,389	17,491	12,594	14,119,385	352,985	275,769	198,554	3,383,774	84,594	66,089	47,584
Takhiatash	1,837,983	31,508	63,017	94,525	1,705,122	29,231	58,461	87,692	508,991	8,726	17,451	26,177	3,186,549	54,627	109,253	163,880	1,001,199	17,163	34,327	51,490
Tahtakupir	4,343,275	74,456	148,912	223,368	4,029,314	69,074	138,148	207,222	625,827	10,728	21,457	32,185	3,330,604	57,096	114,192	171,288	2,019,390	34,618	69,236	103,854
Turtkul	10,183,412	27,277	54,554	81,831	9,447,286	25,305	50,610	75,916	2,730,832	7,315	14,629	21,944	20,357,764	54,530	109,059	163,589	5,281,677	14,147	28,295	42,442
Khujayli	4,810,323	82,463	164,925	247,388	4,462,601	76,502	153,003	229,505	1,005,405	17,236	34,471	51,707	5,984,282	102,588	205,175	307,763	2,481,123	42,534	85,067	127,601
Chimbay	8,851,171	151,734	303,469	455,203	8,211,349	140,766	281,532	422,298	1,899,843	32,569	65,137	97,706	14,526,207	249,021	498,041	747,062	7,079,759	121,367	242,735	364,102
Shumanay	4,105,678	70,383	140,766	211,149	3,808,892	65,295	130,591	195,886	480,761	8,242	16,483	24,725	8,837,370	151,498	302,996	454,493	4,049,399	69,418	138,837	208,255
Elikkala	6,778,645	18,157	36,314	54,471	6,288,639	16,845	33,689	50,534	1,816,549	4,866	9,732	14,597	17,568,700	47,059	94,118	141,177	5,053,997	13,537	27,075	40,612
Total	**93,305,741**	**1,046,374**	**1,920,402**	**2,794,429**	**86,560,974**	**970,735**	**1,781,582**	**2,592,429**	**20,997,782**	**223,580**	**419,873**	**616,166**	**181,751,982**	**1,933,907**	**3,437,613**	**4,941,320**	**60,950,830**	**702,412**	**1,301,724**	**1,901,037**
As % of GDP	*4.42%*	*0.05%*	*0.09%*	*0.13%*	*4.10%*	*0.05%*	*0.08%*	*0.12%*	*0.99%*	*0.01%*	*0.02%*	*0.03%*	*8.60%*	*0.09%*	*0.16%*	*0.23%*	*2.88%*	*0.03%*	*0.06%*	*0.09%*

Source: Authors' estimates.

Annex E: Table 1 Values of Total Production and Estimates of Specific Crop Values Lost Due to Inaction to Restore the Aralkum (cont'd)

District	Value of Total Production Lost Due to SDS from the Aralkum ($)												Share in Value of Total Production of All Crops (%)		
	Fruits				Grapes				Total						
	Value of Total Production ($)	Loss: Lower Bound ($)	Loss: Average ($)	Loss: Upper Bound ($)	Value of Total Production ($)	Loss: Lower Bound ($)	Loss: Average ($)	Loss: Upper Bound ($)	Value of Total Production ($)	Loss: Lower Bound ($)	Loss: Average ($)	Loss: Upper Bound ($)	Lower Bound	Average	Upper Bound
Nukus City	300,077	5,144	10,288	15,433	246,445	4,225	8,450	12,674	4,511,513	77,340	154,680	232,021	1.71%	3.43%	5.14%
Amudaryo	23,496,251	62,936	125,873	188,809	2,279,028	6,105	12,209	18,314	121,834,507	326,342	652,685	979,027	0.27%	0.54%	0.80%
Beruniy	11,198,197	29,995	59,990	89,986	1,726,287	4,624	9,248	13,872	59,270,345	158,760	317,520	476,280	0.27%	0.54%	0.80%
Karauzyak	1,102,400	18,898	37,797	56,695	177,206	3,038	6,076	9,113	18,083,443	310,002	620,004	930,006	1.71%	3.43%	5.14%
Kegeyli	3,219,466	55,191	110,382	165,573	292,213	5,009	10,019	15,028	22,338,568	382,947	765,894	1,148,841	1.71%	3.43%	5.14%
Kungrad	1,122,744	19,247	38,494	57,741	975,217	16,718	33,436	50,154	25,718,385	440,887	881,773	1,322,660	1.71%	3.43%	5.14%
Kanlykul	718,404	12,315	24,631	36,946	185,420	3,179	6,357	9,536	16,761,501	287,340	574,680	862,020	1.71%	3.43%	5.14%
Moynaq	146,224	14,622	29,245	43,867	15,256	1,526	3,051	4,577	4,257,121	425,712	851,424	1,277,136	10.00%	20.00%	30.00%
Nukus	1,486,396	37,160	29,031	20,902	517,534	12,938	10,108	7,278	31,306,771	782,669	611,460	440,251	2.50%	1.95%	1.41%
Takhiatash	690,430	11,836	23,672	35,508	257,007	4,406	8,812	13,217	9,187,281	157,496	314,993	472,489	1.71%	3.43%	5.14%
Tahtakupir	1,097,314	18,811	37,622	56,433	627,848	10,763	21,526	32,289	16,073,571	275,547	551,094	826,641	1.71%	3.43%	5.14%
Turtkul	8,463,177	22,669	45,338	68,008	1,117,217	2,993	5,985	8,978	57,581,365	154,236	308,472	462,707	0.27%	0.54%	0.80%
Khujayli	1,907,266	32,696	65,392	98,088	485,848	8,329	16,658	24,986	21,136,848	362,346	724,692	1,087,038	1.71%	3.43%	5.14%
Chimbay	3,992,544	68,444	136,887	205,331	485,848	8,329	16,658	24,986	45,046,721	772,230	1,544,459	2,316,689	1.71%	3.43%	5.14%
Shumanay	1,088,413	18,659	37,317	55,976	123,222	2,112	4,225	6,337	22,493,736	385,607	771,214	1,156,821	1.71%	3.43%	5.14%
Elikkala	5,801,904	15,541	31,082	46,622	969,350	2,596	5,193	7,789	44,277,785	118,601	237,202	355,804	0.27%	0.54%	0.80%
Total	**65,831,207**	**444,165**	**843,041**	**1,241,917**	**10,480,947**	**96,889**	**178,010**	**259,130**	**519,879,462**	**5,418,062**	**9,882,245**	**14,346,429**	**1.04%**	**1.90%**	**2.76%**
As % of GDP	*3.12%*	*0.02%*	*0.04%*	*0.06%*	*0.50%*	*0.00%*	*0.01%*	*0.01%*	*24.61%*	*0.26%*	*0.47%*	*0.68%*			

Source: Authors' estimates.

Annex Table E.2 Summary of Health Impacts of SDS from the Aralkum—Lower Bound

District	Nukus City	Amudaryo	Beruniy	Karauzyak	Kegeyli	Kungrad	Kanlykul	Moynaq	Nukus	Takhiatash	Tahtakupir	Turtkul	Khujayli	Chimbay	Shumanay	Elikkala	Total for Karakalpakstan
Total GDP in 2019 (billion $)	**0.3559**	**0.2206**	**0.2120**	**0.0592**	**0.1011**	**0.1450**	**0.0569**	**0.0353**	**0.0555**	**0.0823**	**0.0451**	**0.2376**	**0.1369**	**0.1302**	**0.0629**	**0.1764**	**2.1129**
Mortality Due to Ambient Air Pollution (AAP) Caused by SDS from the Aralkum																	
Cost High, $, billion	0.0003	0.0000	0.0000	0.0001	0.0002	0.0001	0.0001	0.0003	0.0001	0.0001	0.0000	0.0000	0.0002	0.0002	0.0001	0.0000	**0.0015**
Cost Low, $, billion	0.0001	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0000	0.0000	**0.0005**
Average Cost, $, billion	0.0002	0.0000	0.0000	0.0000	0.0001	0.0001	0.0000	0.0002	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0000	0.0000	**0.0010**
Morbidity (Assumed to be 10% of Mortality Value)																	
Cost High, $, billion	0.0000	0.0000	0.0000	5.282E-06	1.61E-05	1.034E-05	6.976E-06	2.53E-05	5.37E-06	7.4336E-06	4.5124E-06	0	1.609E-05	1.735E-05	7.125E-06	0	**0.0001**
Cost Low, $, billion	0.0000	0	0	1.652E-06	5.04E-06	3.235E-06	2.182E-06	7.92E-06	1.68E-06	2.325E-06	1.4113E-06	0	5.033E-06	5.427E-06	2.228E-06	0	**0.0000**
Average Cost, $, billion	0.0000	0	0.0000	3.467E-06	1.06E-05	6.788E-06	4.579E-06	1.66E-05	3.53E-06	4.8793E-06	2.9619E-06	0	1.056E-05	1.139E-05	4.676E-06	0	**0.0001**
Total Health Cost of AAP Due to SDS from the Aralkum																	
Cost High, $, billion	0.0003	0.0000	0.0000	0.0001	0.0002	0.0001	0.0001	0.0003	0.0001	0.0001	0.0000	0.0000	0.0002	0.0002	0.0001	0.0000	**0.0016**
Cost Low, $, billion	0.0001	0.0000	0.0000	1.817E-05	0.0001	0.0000	0.0000	0.0001	1.85E-05	2.5576E-05	1.5525E-05	0.0000	0.0001	0.0001	0.0000	0.0000	**0.0005**
Average Cost, $, billion	0.0002	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0002	0.0000	0.0001	0.0000	0.0000	0.0001	0.0001	0.0001	0.0000	**0.0011**
% GDP	**0.055%**	**0.000%**	**0.000%**	**0.064%**	**0.115%**	**0.051%**	**0.089%**	**0.518%**	**0.070%**	**0.065%**	**0.072%**	**0.000%**	**0.085%**	**0.096%**	**0.082%**	**0.000%**	**0.051%**
Average Cost in $	**194,560**	**-**	**-**	**38,135**	**116,303**	**74,672**	**50,366**	**182,815**	**38,794**	**53,673**	**32,580**	**-**	**116,179**	**125,285**	**51,441**	**-**	**1,074,803**
Total Number of Deaths Due to SDS from the Aralkum																	
Deaths IHD	0.11	0.0000	0.0000	0.2965	1.2117	0.3905	0.1174	1.2357	0.4344	0.2684	0.3858	0.0000	0.4158	0.9052	0.1178	0.0000	**5.8875**
Deaths stroke	0.86	0.0000	0.0000	0.1267	0.0000	0.1137	0.1078	0.0693	0.0316	0.2015	0.0000	0.0000	0.4290	0.3395	0.1623	0.0000	**2.4460**
Deaths COPD	0.01	0.0000	0.0000	0.0000	0.0000	0.1611	0.3481	0.1072	0.0093	0.0475	0.0000	0.0000	0.3736	0.2696	0.3064	0.0000	**1.6325**
Deaths LC	0.59	0.0000	0.0000	0.0108	0.1905	0.0070	0.0000	0.4287	0.0034	0.0071	0.0000	0.0000	0.0143	0.0000	0.0000	0.0000	**1.2539**
Deaths LRI	0.63	0.0000	0.0000	0.0034	0.0000	0.0069	0.0000	0.2494	0.0000	0.0237	0.0000	0.0000	0.0033	0.0000	0.0000	0.0000	**0.9160**
Deaths Diabetes 2	0.20	0.0000	0.0000	0.0330	0.0329	0.2421	0.0482	0.1654	0.0000	0.1140	0.0161	0.0000	0.1975	0.0315	0.0482	0.0000	**1.1256**
Total	**2.40**	**0.0000**	**0.0000**	**0.4705**	**1.4350**	**0.9213**	**0.6214**	**2.2557**	**0.4787**	**0.6622**	**0.4020**	**0.0000**	**1.4335**	**1.5458**	**0.6347**	**0.0000**	**13.2615**

Source: Authors' estimates.

Annex Table E.3 Summary of Health Impacts of SDS from the Aralkum—Average

District	Nukus City	Amudaryo	Beruniy	Karauzyak	Kegeyli	Kungrad	Kanlykul	Moynaq	Nukus	Takhiatash	Tahtakupir	Turtkul	Khujayli	Chimbay	Shumanay	Elikkala	Total for Karakalpakstan
Total GDP in 2019 (billion $)	**0.3559**	**0.2206**	**0.2120**	**0.0592**	**0.1011**	**0.1450**	**0.0569**	**0.0353**	**0.0555**	**0.0823**	**0.0451**	**0.2376**	**0.1369**	**0.1302**	**0.0629**	**0.1764**	**2.1129**
Mortality Due to Ambient Air Pollution (AAP) Caused by SDS from the Aralkum																	
Cost High, $, billion	0.0005	0.0000	0.0000	0.0001	0.0003	0.0002	0.0001	0.0003	0.0001	0.0001	0.0001	0.0000	0.0003	0.0003	0.0001	0.0000	**0.0024**
Cost Low, $, billion	0.0002	0.0000	0.0000	0.0000	0.0001	0.0001	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0000	0.0000	**0.0007**
Average Cost, $, billion	0.0004	0.0000	0.0000	0.0001	0.0002	0.0001	0.0001	0.0002	0.0001	0.0001	0.0000	0.0000	0.0002	0.0002	0.0001	0.0000	**0.0016**
Morbidity (Assumed to be 10% of Mortality Value)																	
Cost High, $, billion	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	**0.0002**
Cost Low, $, billion	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	**0.0001**
Average Cost, $, billion	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	**0.0002**
Total Health Cost of AAP Due to SDS from the Aralkum																	
Cost High, $, billion	0.0006	0.0000	0.0000	0.0001	0.0003	0.0002	0.0001	0.0003	0.0001	0.0001	0.0001	0.0000	0.0003	0.0003	0.0001	0.0000	**0.0026**
Cost Low, $, billion	0.0002	0.0000	0.0000	0.0000	0.0001	0.0001	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0000	0.0000	**0.0008**
Average Cost, $, billion	0.0004	0.0000	0.0000	0.0001	0.0002	0.0001	0.0001	0.0002	0.0001	0.0001	0.0000	0.0000	0.0002	0.0002	0.0001	0.0000	**0.0017**
% GDP	**0.109%**	**0.000%**	**0.000%**	**0.099%**	**0.184%**	**0.085%**	**0.149%**	**0.608%**	**0.104%**	**0.105%**	**0.108%**	**0.000%**	**0.138%**	**0.149%**	**0.135%**	**0.000%**	**0.081%**
Average Cost in $	**1,646,787**	**749,569**	**1,298,989**	**145,219**	**516,790**	**266,228**	**221,204**	**246,576**	**150,462**	**207,285**	**120,557**	**474,133**	**456,561**	**498,820**	**213,809**	**646,808**	**1,714,850**
Total Number of Deaths Due to SDS from the Aralkum																	
Deaths IHD	0.16	0.00	0.00	0.44	1.79	0.58	0.17	1.37	0.64	0.40	0.57	0.00	0.62	1.34	0.17	0.00	**8.26**
Deaths stroke	1.28	0.00	0.00	0.19	0.00	0.17	0.16	0.08	0.05	0.30	0.00	0.00	0.64	0.51	0.24	0.00	**3.62**
Deaths COPD	0.02	0.00	0.00	0.00	0.00	0.29	0.62	0.13	0.02	0.08	0.00	0.00	0.67	0.48	0.55	0.00	**2.85**
Deaths LC	1.38	0.00	0.00	0.03	0.44	0.02	0.00	0.57	0.01	0.02	0.00	0.00	0.03	0.00	0.00	0.00	**2.49**
Deaths LRI	1.57	0.00	0.00	0.01	0.00	0.02	0.00	0.33	0.00	0.06	0.00	0.00	0.01	0.00	0.00	0.00	**2.00**
Deaths Diabetes 2	0.36	0.00	0.00	0.06	0.06	0.45	0.09	0.17	0.00	0.21	0.03	0.00	0.36	0.06	0.09	0.00	**1.94**
Total	**4.77**	**0.00**	**0.00**	**0.72**	**2.30**	**1.52**	**1.04**	**2.65**	**0.72**	**1.07**	**0.60**	**0.00**	**2.33**	**2.39**	**1.05**	**0.00**	**21.16**

Source: Authors' estimates.

Annex Table E.4 Summary of Health Impacts of SDS from the Aralkum—Upper Bound

District	Nukus City	Amudaryo	Beruniy	Karauzyak	Kegeyli	Kungrad	Kanlykul	Moynaq	Nukus	Takhiatash	Tahtakupir	Turtkul	Khujayli	Chimbay	Shumanay	Elikkala	Total for Karakalpakstan
Total GDP in 2019 (billion $)	**0.3559**	**0.2206**	**0.2120**	**0.0592**	**0.1011**	**0.1450**	**0.0569**	**0.0353**	**0.0555**	**0.0823**	**0.0451**	**0.2376**	**0.1369**	**0.1302**	**0.0629**	**0.1764**	**2.1129**
Mortality Due to Ambient Air Pollution (AAP) Caused by SDS from the Aralkum																	
Cost High, $, billion	0.0008	0.0000	0.0000	0.0001	0.0004	0.0002	0.0002	0.0003	0.0001	0.0002	0.0001	0.0000	0.0004	0.0004	0.0002	0.0000	**0.0033**
Cost Low, $, billion	0.0003	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0000	0.0001	0.0000	0.0000	0.0001	0.0001	0.0001	0.0000	**0.0010**
Average Cost, $, billion	0.0005	0.0000	0.0000	0.0001	0.0002	0.0002	0.0001	0.0002	0.0001	0.0001	0.0001	0.0000	0.0002	0.0002	0.0001	0.0000	**0.0021**
Morbidity (Assumed to be 10% of Mortality Value)																	
Cost High, $, billion	0.0001	0.0000	0.0000	1.09682E-05	3.5441E-05	2.36864E-05	1.6477E-05	3.4151E-05	1.0685E-05	1.6588E-05	8.98895E-06	0	3.6237E-05	3.6259E-05	1.64595E-05	0	**0.0003**
Cost Low, $, billion	0.0000	0	0	3.43056E-06	1.1085E-05	7.40849E-06	5.1537E-06	1.0681E-05	3.3421E-06	5.18829E-06	2.81151E-06	0	1.1334E-05	1.1341E-05	5.14809E-06	0	**0.0001**
Average Cost, $, billion	0.0001	0	0.0000	7.19937E-06	2.3263E-05	1.55475E-05	1.0816E-05	2.2416E-05	7.0136E-06	1.08881E-05	5.90023E-06	0	2.3785E-05	2.38E-05	1.08038E-05	0	**0.0002**
Total Health Cost of AAP Due to SDS from the Aralkum																	
Cost High, $, billion	0.0009	0.0000	0.0000	0.0001	0.0004	0.0003	0.0002	0.0004	0.0001	0.0002	0.0001	0.0000	0.0004	0.0004	0.0002	0.0000	**0.0036**
Cost Low, $, billion	0.0003	0.0000	0.0000	3.77362E-05	0.0001	0.0001	0.0001	0.0001	3.6763E-05	5.70712E-05	3.09266E-05	0.0000	0.0001	0.0001	0.0001	0.0000	**0.0011**
Average Cost, $, billion	0.0006	0.0000	0.0000	0.0001	0.0003	0.0002	0.0001	0.0002	0.0001	0.0001	0.0001	0.0000	0.0003	0.0003	0.0001	0.0000	**0.0024**
% GDP	**0.163%**	**0.000%**	**0.000%**	**0.134%**	**0.253%**	**0.118%**	**0.209%**	**0.698%**	**0.139%**	**0.146%**	**0.144%**	**0.000%**	**0.191%**	**0.201%**	**0.189%**	**0.000%**	**0.111%**
Average Cost in $	**579,143**	**-**	**-**	**79,193**	**255,894**	**171,022**	**118,971**	**246,576**	**77,150**	**119,770**	**64,903**	**-**	**261,637**	**261,796**	**118,842**	**-**	**2,354,896**
Total Number of Deaths Due to SDS from the Aralkum																	
Deaths IHD	0.21	0.0000	0.0000	0.5808	2.3744	0.7663	0.2305	1.5011	0.8529	0.5266	0.7574	0.0000	0.8152	1.7789	0.2318	0.0000	**10.6287**
Deaths stroke	1.71	0.0000	0.0000	0.2543	0.0000	0.2255	0.2141	0.0864	0.0627	0.4018	0.0000	0.0000	0.8570	0.6744	0.3183	0.0000	**4.7997**
Deaths COPD	0.02	0.0000	0.0000	0.0000	0.0000	0.4136	0.8936	0.1471	0.0238	0.1220	0.0000	0.0000	0.9590	0.6920	0.7865	0.0000	**4.0623**
Deaths LC	2.16	0.0000	0.0000	0.0395	0.6945	0.0256	0.0000	0.7131	0.0125	0.0258	0.0000	0.0000	0.0523	0.0000	0.0000	0.0000	**3.7219**
Deaths LRI	2.52	0.0000	0.0000	0.0136	0.0000	0.0276	0.0000	0.4153	0.0000	0.0945	0.0000	0.0000	0.0132	0.0000	0.0000	0.0000	**3.0794**
Deaths Diabetes 2	0.53	0.0000	0.0000	0.0889	0.0885	0.6516	0.1297	0.1793	0.0000	0.3069	0.0435	0.0000	0.5316	0.0849	0.1297	0.0000	**2.7640**
Total	**7.15**	**0.0000**	**0.0000**	**0.9771**	**3.1574**	**2.1102**	**1.4679**	**3.0424**	**0.9519**	**1.4778**	**0.8008**	**0.0000**	**3.2282**	**3.2302**	**1.4663**	**0.0000**	**29.0559**

Source: Authors' estimates.

Annex F: Total Impacts

Annex Table F.1 Annual Values of On-Site and Off-Site Ecosystem Services Under Different Rehabilitation Scenarios—Lower Bound

Scenarios		Annual Losses ($)			Annual Total Benefits of On-Site and Off-Site Ecosystem Services Compared to the Base Case (Scenario 1)					Average NPV of Action ($/year/ha)	Annual BCR (assuming a 20-year period)
		On-Site	Off-Site								
		Ecosystem Services	Crop Yields	Health	Total ($)	Value Gained from Action ($/year)	Average PV of Action ($/year/ha)	As % of Karakalpakstan GDP	Annual Cost of Action ($, million)		
Scenario 1 (Current Scenario): 90% Bare (-) and 10% Bare (+)	*Min*	24,384,066	5,418,062	1,074,803	**30,876,931**						
	Avg	24,384,066	9,882,245	1,714,850	**35,981,161**						
	Max	24,384,066	14,346,429	2,354,896	**41,085,391**						
Scenario 2: 50% Shrub (-) and 50% Shrub (+)	*Min*	17,059,695	2,977,691	724,218	**20,761,604**	10,115,327	7.65	0.48%	23,104,132	(9.82)	0.44
	Avg	17,059,695	5,085,176	995,959	**23,140,830**	12,840,332	8.42	0.61%	23,104,132	(9.06)	0.56
	Max	17,059,695	7,192,661	1,267,700	**25,520,055**	15,565,336	11.77	0.74%	23,104,132	(5.70)	0.67
Scenario 3: 50% Tree (-) and 50% Tree (+)	*Min*	9,710,417	2,941,456	724,218	**13,376,091**	17,500,839	13.24	0.83%	23,104,132	(4.24)	0.76
	Avg	9,710,417	5,014,055	995,959	**15,720,431**	20,260,730	14.03	0.96%	23,104,132	(3.45)	0.88
	Max	9,710,417	7,086,654	1,267,700	**18,064,771**	23,020,620	17.41	1.09%	23,104,132	(0.06)	1.00
Scenario 4: (best possible scenario): 100% Tree (+)	*Min*	-	2,606,582	159,166	**2,765,747**	28,111,184	21.26	1.33%	23,104,132	3.79	1.22
	Avg	-	4,356,036	713,433	**5,069,468**	30,911,693	22.08	1.46%	23,104,132	4.61	1.34
	Max	-	6,105,490	1,267,700	**7,373,190**	33,712,202	25.50	1.60%	23,104,132	8.02	1.46

Source: Authors' estimates.

Annex Table F.2 Annual Values of On-Site and Off-Site Ecosystem Services Under Different Rehabilitation Scenarios—Upper Bound

Scenarios		Annual Losses ($)			Annual Total Benefits of On-Site and Off-Site Ecosystem Services Compared to the Base Case (Scenario 1)					Average NPV of Action ($/year/ha)	Annual BCR (assuming a 20-year period)
		On-Site	Off-Site								
		Ecosystem Services	Crop Yields	Health	Total ($)	Value Gained from Action ($/year)	Average PV of Action ($/year/ha)	As % of Karakalpakstan GDP	Annual Cost of Action ($, million)		
Scenario 1 (Current Scenario): 90% Bare (-) and 10% Bare (+)	*Min*	34,968,151	5,418,062	1,074,803	**41,461,016**						
	Avg	34,968,151	9,882,245	1,714,850	**46,565,246**						
	Max	34,968,151	14,346,429	2,354,896	**51,669,476**						
Scenario 2: 50% Shrub (-) and 50% Shrub (+)	*Min*	24,646,463	2,977,691	724,218	**28,348,372**	13,112,643	9.92	0.62%	24,300,409	(8.46)	0.54
	Avg	24,646,463	5,085,176	995,959	**30,727,598**	15,837,648	10.68	0.75%	24,300,409	(7.70)	0.65
	Max	24,646,463	7,192,661	1,267,700	**33,106,824**	18,562,652	14.04	0.88%	24,300,409	(4.34)	0.76
Scenario 3: 50% Tree (-) and 50% Tree (+)	*Min*	13,562,834	2,941,456	724,218	**17,228,508**	24,232,507	18.33	1.15%	24,300,409	(0.05)	1.00
	Avg	13,562,834	5,014,055	995,959	**19,572,848**	26,992,397	19.12	1.28%	24,300,409	0.74	1.11
	Max	13,562,834	7,086,654	1,267,700	**21,917,188**	29,752,288	22.50	1.41%	24,300,409	4.12	1.22
Scenario 4: (best possible scenario): 100% Tree (+)	*Min*	-	2,606,582	159,166	**2,765,747**	38,695,268	29.27	1.83%	24,300,409	10.89	1.59
	Avg	-	4,356,036	713,433	**5,069,468**	41,495,777	30.09	1.96%	24,300,409	11.71	1.71
	Max	-	6,105,490	1,267,700	**7,373,190**	44,296,287	33.50	2.10%	24,300,409	15.12	1.82

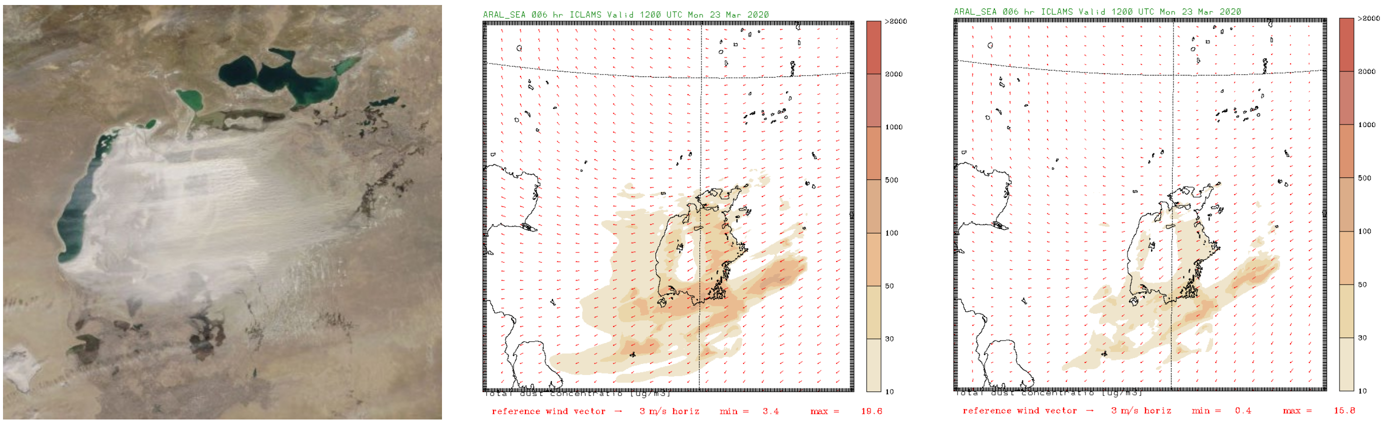
Source: Authors' estimates.

Annex G: Off-Site SDS Impact Assessment Using Regional Atmospheric Modeling System (RAMS): A Single Event Case Study

Activity/Methodology

Off-site SDS impact assessment was pursued through atmospheric modeling using RAMS (Cotton et al., 2003; Pielke et al., 1992) to simulate a selected SDS event observed on March 23, 2020 across the Aralkum (Annex Map G.1; left). RAMS generated the atmospheric wind trajectories and the consequential pick-up and suspension of surface sediments originating from the dry Aral Seabed and its surrounding areas. The single event analysis (Annex Map G.1) represents the SDS event observed through remote sensing and reveals: i) a reasonable match with the observation, and ii) a significant effect of hypothetical vegetation cover mimicking e.g., Scenario 3.2 (Annex Map G.1; right) tree- and shrub-based rehabilitation. The single-event atmospheric simulation was pursued in a parallel attempt to the simplistic radial dispersion modeling undertaken – and was used for visual verification of dust dispersion processes and area of impact estimation. Coupling the high-resolution on-site wind erosion model with the atmospheric trajectory modeling eventually allows a more detailed assessment of SDS fluxes and their potential impacts per specific context.

Annex Map G.1 RAMS Simulation of Dust Concentration and Wind Field at 40 m Height During March 23, 2020 SDS Event



Source: NASA MODIS (left); Institute of Accelerating Systems and Applications (IASA) affiliated with the Technical University of Athens, under Prof. George Kallos and his students, co-advised by Utrecht University and ICARDA (middle and right).
Note: Remote sensing image of the SDS event on March 23, 2020 (left). Degraded/actual scenario of dry Aral Seabed (middle). Rehabilitated scenario with 50% shrub and vegetation cover (comparable to Scenario 3.2 Tree (+) tree- and shrub-based established ecosystem) (right).


68
UNIVERSAL

THE WORLD BANK
IBRD • IDA | WORLD BANK GROUP

www.worldbank.org