Remote sensing and ground based monitoring of afforestation measures on the desiccated Aral Sea bed – Inventory and impact assessment of a project dedicated to the mitigation of an ecologic disaster

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Abstract

The desiccation of the Aral Sea is one of the most severe man-made ecological disasters. With increasing aridity of the climate and the presence of natural aerosol sources, air pollution is considered to advance in this region. As a potential countermeasure to reduce the erosion of dust and salts, different afforestation measures were tested within a pilot project conducted by the *Deutsche Gesellschaft für technische Zusammenarbeit* (GTZ). This study describes a remote sensing based approach for the detailed inventory and characterization of the afforestations in a test area southeast of the Aral Sea. Visual interpretation of very high resolution satellite images (SPOT-5 2,5m, acquired in 2005 and 2006) was used to identify the geographic location, spatial extent and pattern and planting success of the vegetation sites. Overall, 70 afforestation patches could be demarcated, covering a total area of 9188 hectares. Growth success shows a strong variation among the 70 patches due to heterogeneity in age, site conditions (spectral surface characteristics) and the resolution of the utilized satellite data. 60% of the inventoried afforestation patches show an Eastern planting direction, perpendicular to prevailing winds from North. This indicates a good suitability of these patches as windbreaks, which was tested in two representative sites. A network of anemometer stations and BSNE saltation samplers was used in order to assess the impact of the plantation measures on wind speed and sand transport. The results indicate a positive reducing effect of the created plant cover on wind speed and soil erosion.

1. Introduction

The desiccation of the Aral Sea since the 1960s is considered of one of the most severe man-made ecological disasters in history (UNESCO, Annual report 1992). With the recession of the sea, a huge new saline desert emerged at the intermission of the two great sand deserts of Central Asia, Kara Kum and Kyzyl Kum, which is nowadays referred to as the “Aral Kum”. The loss of the water body as a buffer led an intense aridization of the climate in the region, expressed by hotter summer and colder winter temperatures and less precipitation. With the increasing aridity of the climate and the presence of natural aerosol sources, air pollution is also considered to advance in this region by the export of aeolian dust and salt from the exposed seabed.

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The GTZ-Project „Stabilization of the desiccated Aral Sea bed in Central Asia" was established as a multilateral development cooperation project in Kazakhstan and Uzbekistan in the year 2000. The project goals were the mitigation of the negative effects of desertification and dust export of the desiccated Aral Sea by a refinement of the local afforestation techniques in the states bordering the Aral Sea, which were developed during soviet times. Through the use of machinery and new planting techniques, as well as a scientific screening of suitable plant material, a sustainable large scale afforestation of the sea bed should be realized in order to stabilize and enhance the natural overgrowing of the newly formed desert.

Due to the lack of a scientific documentation of the achievements of the project, a monitoring component was introduced in 2005. The objective of this component was the assessment of the planting success and impact of the afforestation measures by the use of remote sensing and ground based methods. The results of these activities are presented in this paper.

2. Study area

In an agreement between GTZ and the Uzbek government, the project territory shown in Fig. 1 was determined on the Uzbek part of the desiccated seabed. The territory is located between the Dzhiltyrbas wetland and Kokdarya river in the Muinak rayon of Karakalpakstan. The area totals at 80.000 ha and features a multitude of different landscape and soil types on the seabed, including vast dune fields, sand sheets and various kinds of solonchak (salt soil) areas. According to the assessment of Dukhovny et al. (2008), the major part of the territory is located in highly unstable landscapes with a high ecological hazard degree in terms of desertification and aeolian erosion.

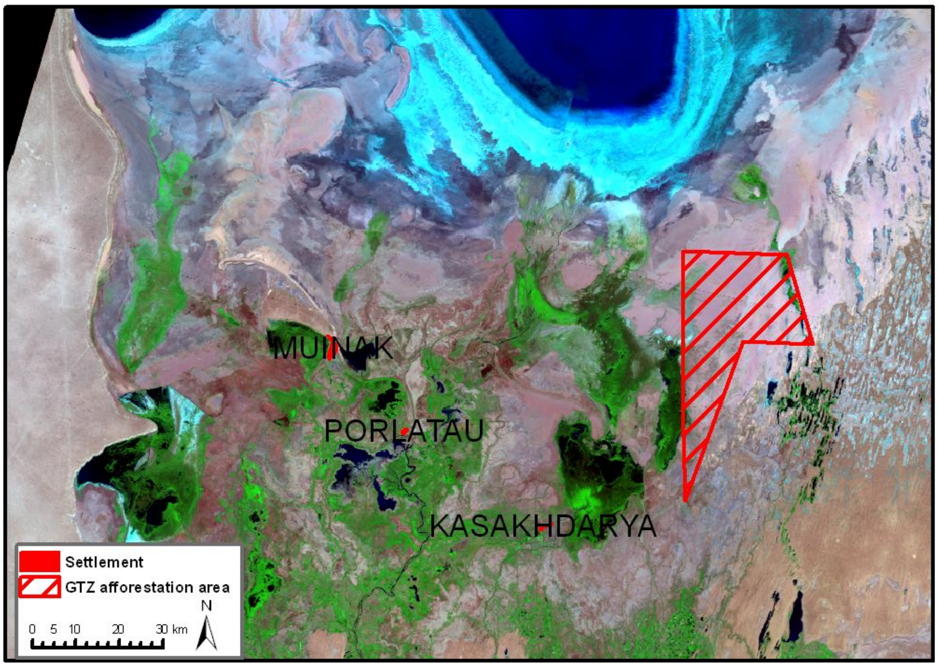


Fig. 1: Location of the GTZ afforestation area

3. Data and methods

3.1. Preprocessing of the satellite data

For this study, the satellite images of the French SPOT-5 (**S**ystème **P**our l'**O**bservation de la **T**erre) listed in Tab. 1 were used:

Tab. 1: Satellite scenes used in this study

Sensor	Acquisition date	Spatial resolution	Processing level
PAN	21.07.2005	2,5m	2A
XS	21.07.2005	10m	2A
PAN	05.08.2006	2,5m	1A
XS	05.08.2006	10m	1A

In order to improve the spatial accuracy, the multispectral data was geometrically corrected by the use of GPS-measured ground control points (GCPs) and an orthorectification of the level 1A datasets was performed by the use of a DEM (digital elevation model).

Afterwards, a semi-automatic geometric scene matching was applied to fit the panchromatic with the multispectral scenes (as described in Hill & Mehl 2003).

All datasets were corrected for atmospheric distortions by the procedure described by Richter (2006). The last preprocessing step was a pan-sharpening of the data, i.e. a data fusion procedure to merge the high-resolution panchromatic images with the lower resolution multispectral image into a high resolution multispectral data set. The "Gram-Schmitt spectral sharpening" procedure implemented in the software package "ENVI" (ITTVIS Inc.) was chosen.

3.2. Analysis of the satellite data

After the pre-processing, the SPOT-5 data was visually interpreted for the detection of the afforestation patches. The first step was the establishment of a GIS database which contains the acquired information. Tab. 2 shows the created datasets and their attributes:

Tab. 2: Attributes of the GIS database

Content	Type	Attributes
Afforestation patches	Polygon	Center coordinates [UTM], area [ha], plantation line length [m]
		Planting direction [°]
Afforestation lines	Polyline	Length [m],
		Growth [successful/not successful],
		Planting direction [°]
Natural shrubs	Point	-

These datasets were created by on-screen digitizing of the satellite scenes. First, all afforestation patches were demarcated. All in all, 70 patches could be identified, covering a total area of 9188 hectares. These patches are not aligned to the exact extent of the visible planting lines, as the assumption is that the patches were originally planned in a more or less rectangular shape.

The plantation lines were considered as belonging to one afforestation patch if the criteria direction, spacing and planting pattern were homogeneous. The planting lines were digitized and attributed with planting success.

The natural shrubs were captured in a point dataset, with no additional attributes. The criteria for an object to be considered as a naturally grown shrub were the size and spectral value of the potential shrub differing from those of the planting lines or a location outside the typical planting line pattern.

After all afforestations were digitized and quality checked for errors of omission and commission, a statistical analysis was applied to the planting line dataset.

Line segment length was captured and statistics for successful and unsuccessful line segments were calculated (sum, mean, standard deviation of segment length). Planting direction was measured and the arithmetic mean and standard deviation were calculated for each afforestation patch. Additionally, a growth success rate was calculated by Eq.1.

Eq.1: $$gs = \frac{l_{succ}}{l_{total}}$$

gs: growth success

l_{succ}: length of successful line segments

l_{total}: total planting line length

3.3. Wind and erosion measurements

For the assessment of the local wind conditions (wind speed and direction) and the aeolian sand transport, a network of metrological stations and sand trap clusters was installed within the project territory for the 2006 summer season.

Fig. 2 shows the spatial layout of the facilities. A total of 5 meteostations were installed on different land cover types, equipped with anemometers (Thies Clima Anemometer Compact) in three measurement heights (0,5m, 2m and 10m) and one wind vane (Vector Instruments W200P). Delta-T GP1 data loggers were programmed to log the sensor measurements in a 10 sec interval. The power supply was realized by 12V lead-acid batteries, which granted a 6 week measuring cycle until a data readout and battery change were necessary. In order to maintain a security buffer and prevent data weeks.

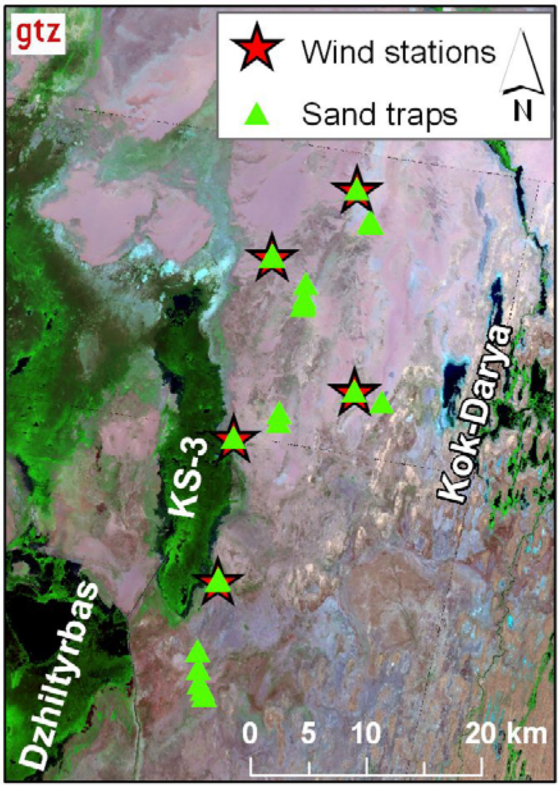


Fig. 2: Spatial layout of the wind and erosion measurements

Fig. 3: Wind station and sand traps

The 23 saltation samplers were designed in the concept of the BSNE (Big Spring Number Eight) sampler as described by Fryrear (1986), Zobeck et al. (2003) and Zobeck &Van Pelt (2006) (Fig. 3). These samplers were installed on posts into sampler clusters, with measurement heights 0.1, 0.4, 0.65 and 1.5m. The locations were also spread over the project territory, covering all available surface and vegetation cover types.

The samplers were emptied on a monthly basis, and the collected sediment was characterized by weight (quantity) and texture where possible (dependent on sufficient quantity collected).

Apart from the characterization of material transport on the different surface types, one central objective of this investigation was the impact assessment of the afforestation measures on soil erosion. Therefore, some of the 23 samplers were set-up in north-south transects (aligned with the dominant wind direction) covering individual plantations of *Haloxylon aphyllum* or *Aristida karelini*. A comparison of the quantity of the caught sediment on vegetated and non-vegetated surfaces allowed an impact estimation of the afforestations on material transport.

A similar strategy was chosen in order to estimate the influence of *Haloxylon aphyllum* plantations on wind speed. Therefore, the measurements for one month (July 2006) on a non-vegetated surface were compared to the measurements from a station located within a five year old afforestation.

4. Results

4.1. Remote sensing based inventory of the afforestations

The growth success rate varies greatly, among the afforestation patches as well as within the patches (Fig. 5, Fig. 4). The primary explanation for this variation is the intensive heterogeneity in the site conditions (substrate, groundwater). On the other hand it is also dependent on the total length of planting lines identifiable in the satellite images. It has to be considered that only clearly visible line segments were mapped by the interpreter, whereas areas with no identifiable plantings were not considered in the growth success rate. Planting direction of the afforestation patches also shows a high variation among the patches (Fig. 5).

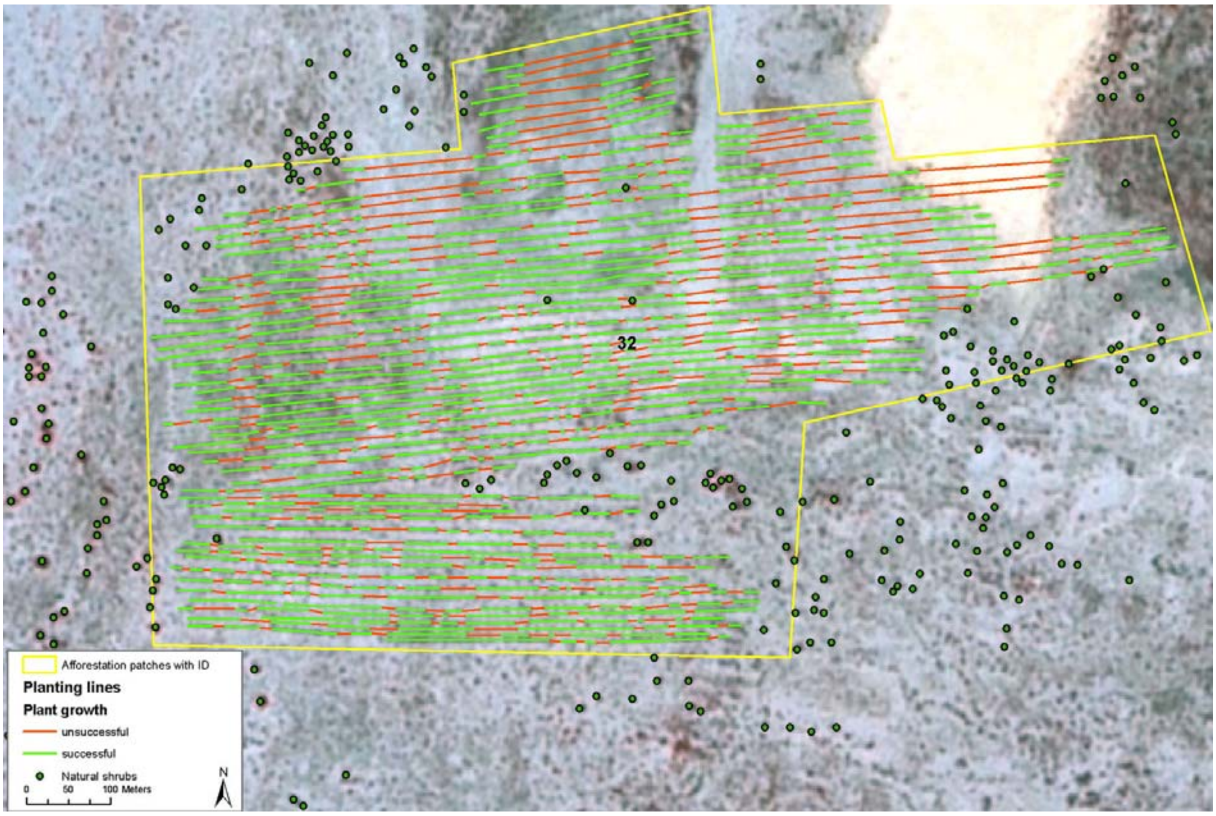
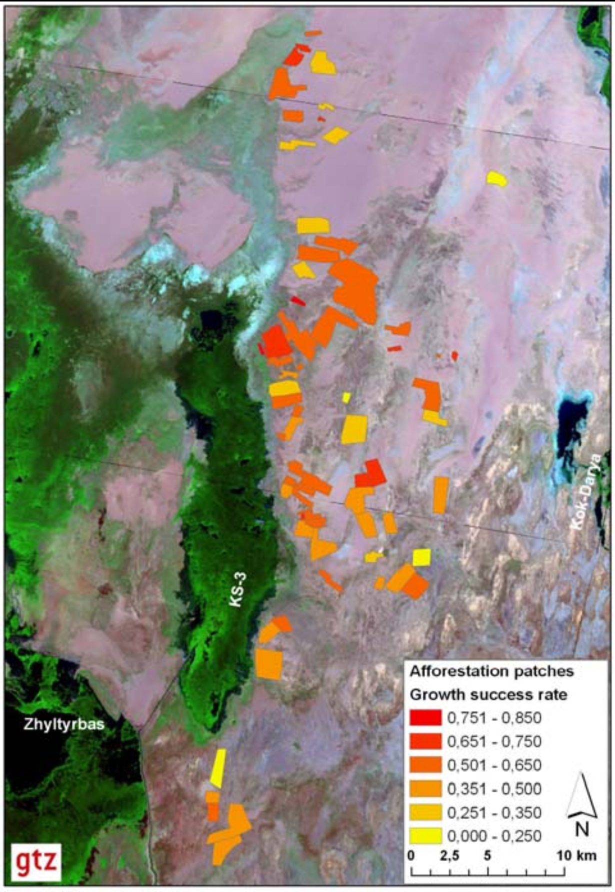


Fig. 4: Afforestation patch with digitized planting lines

The frequency distribution of patch directions indicates that 42 patches are oriented in East (East-Northeast to East-Southeast), 17 in South-East, 7 in North-South and 3 in North-East direction. Considering a prevailing Northern to North-Eastern wind direction estimated for the North of Karakalpakstan (derived from measurements of Muinak and Takhtakupyr meteorological stations during the 2000 dust storm season, as well as long-term and large-scale climatic studies (Wiggs et al. 2003; Kabulow 1990; Kitoh et al. 1993, cited in Letolle & Mainguet 1996) , then the 42 patches in East direction (60% of all patches) are designed approximately perpendicular against this dominant wind direction and thereby serve as suitable wind breaks. The suitability of the orientation of the remaining 40% afforestation patches has not yet been evaluated in detail. Detailed explicit information on the locally occurring wind directions of 2006 shows a rather wide variation of the prevailing erosive winds (speed >6 m/s).


Zhyltyrbas
KS-3
Kok-Darya
Afforestation patches
Growth success rate
0,751 - 0,850
0,651 - 0,750
0,501 - 0,650
0,351 - 0,500
0,251 - 0,350
0,000 - 0,250
N
0 2,5 5 10 km
gtz

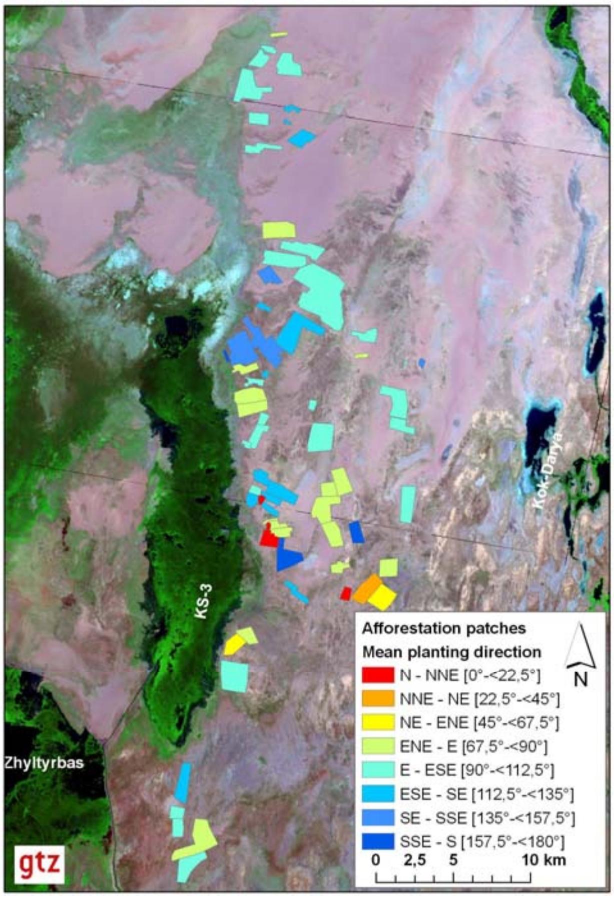

Zhyltyrbas
KS-3
Kok-Darya
Afforestation patches
Mean planting direction
N - NNE [0°-<22,5°]
NNE - NE [22,5°-<45°]
NE - ENE [45°-<67,5°]
ENE - E [67,5°-<90°]
E - ESE [90°-<112,5°]
ESE - SE [112,5°-<135°]
SE - SSE [135°-<157,5°]
SSE - S [157,5°-<180°]
N
0 2,5 5 10 km
gtz

Fig. 5: Distribution of plant establishment rate and planting direction among the afforestations

These distributions can be used to justify variable planting directions, even though a parallel adjustment of the planting lines might induce canalizing effects on the wind. However, detailed assessments on the effect of wind-parallel lines are not available yet and it remains unknown if the possible canalizing overrides the increased surface roughness provided by the afforestations as well as the induced self-overgrowing.

Information about the age of the plantations could not be extracted from the satellite scenes. Therefore, dendro-chronologic methods could be applied in the field to obtain this information.

5. Impact on wind speed and soil erosion

For the impact assessment of the afforestation measures on wind speed, data of two meteorological stations on the desiccated sea bed was compared. One station (N43°49’25”, E60°05’50”) was installed in the center of a Black Saxaul (*Haloxylon aphyllum*) afforestation patch planted in 2001. This particular afforestation site was selected due to several reasons:

- i) it was one of the first afforestations planted by the GTZ project (→ age verified)
- ii) the trees show very healthy growth (height > 2m)
- iii) natural succession and development is already taking place

The second station (N43°52’25”, E60°11’27”) was located 9.3 km East-Northeast, on a non-vegetated flat Solonchak surface. Due to the proximity of the two stations, the “input” wind conditions are assumed to be similar and therefore, the differences in wind speed between the two stations can be linked to the differences in vegetation cover (i.e. the afforestation). Detailed results can be found in Blasch 2007. Fig. 6 shows the profiles of the two wind stations in comparison.

The profile for the station on the non-vegetated area (Fig.06b) displays a very similar magnitude of the measurements in the three measure heights. Especially the plots for 0.5m and 2m overlay largely. It is also obvious, that even the close-to-surface winds (0.5 and 2m) reach the 6 m/s threshold for erosive winds during the peak times (July 03rd-05th, July 10th-12th, July 25th-27th).

In comparison to this, the profile for station on the afforested site (Fig. 06a) differs in several characteristics. The plots for the different heights have a much smaller overlap, i.e. their wind speed magnitudes differ significantly. Furthermore, the surface near wind speed appears to be reduced in comparison to the measurements on the non-vegetated area.

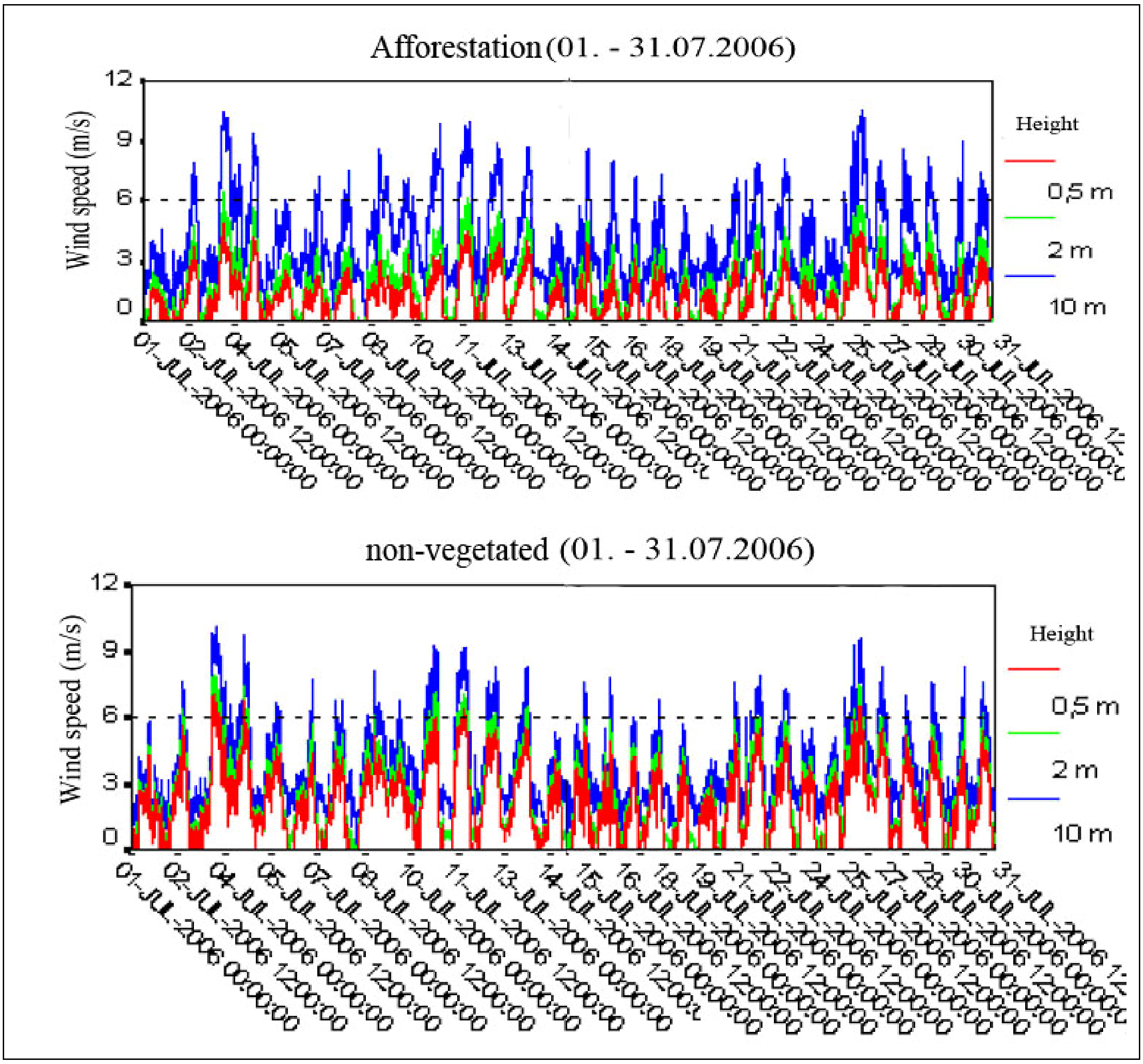


Fig. 6: Wind speed profiles of the two wind stations

These results are further underlined by the statistical measures shown in Tab. 3. While the mean wind speed at 10m is almost identical at the two stations, it is significantly lower at 0.5 and 2m over the vegetated surface. The surface near wind peaks also differ significantly: while the maximum values measured on the non-vegetated surface were 7 m/s (0,5m) and 8 m/s (2m), the peaks in the afforested area were 4.9 m/s (0.5m) and 6.4 m/s (2m), respectively.

Tab. 3: Wind speed characteristics on vegetated and non-vegetated surfaces in July 2006

	$\bar{v}$ **(m/s)**		v_{max} **(m/s)**	
Height	**vegetated**	**Non-vegetated**	**vegetated**	**Non-vegetated**

01st-14th	0.5m	1.2	2.3	4.9	7.0
	2m	1.8	2.8	6.4	8.0
	10m	4.1	3.9	10.5	10.1
15th-31st	0.5m	1.1	2.0	4.5	6.6
	2m	1.6	2.4	5.8	7.6
	10m	3.8	3.5	10.5	9.6

Assuming the general wind conditions to be similar at the two locations, these results indicate the positive (i.e. reducing) effect of the afforestation on wind speed. Thereby, it can be assumed that the *Haloxylon aphyllum* trees also reduce the erosive impact of the wind. In order to underline this second assumption, a transect of three BSNE sediment sampler clusters was established in a N-S orientation right next to the weather station. Fig. 7 shows the situation of the three sand traps among the afforestation area.

Sampler 1:	Sampler 2:	Sampler 3:
North of afforestation	Center of afforestation	South of afforestation
Active barchanoid dune field	2,5m Saxaul on flat dunes/ sand sheet	Flat sand sheet with natural overgrowing

Fig. 7: Situation of the three saltation sampler clusters

The afforested plants are supposed to reduce aeolian erosion in two ways: First of all, they fix the substrate by the development of an extensive root system and secondly, they increase surface roughness and thereby filter out aeolian sediment, which is transported in the air. The amount of the latter was measured in this study by the use of the BSNE samplers, in front of the afforestation, in the center and behind the afforestation, in reference to the dominant N-S wind direction. By collecting the transported sediment through a standardized opening, an estimation of the amount transported in one m² (vertical) was possible (Blasch 2007).

Tab. 4 and Fig. 8 show the results of the measurements for the period May to August.

The table and figure show a clear N-S trend in the sediment transport: the more planting lines are passed, the less sediment is transported. This trend also is visible in the geomorphology in the area: while the northernmost sampler is situated in an active dune field (which indicates very high amounts of sand transport), sampler 2 (center of plantation) stands on a slightly undulating sand sheet. Finally, sampler 3 is situated in a flat terrain, which can be considered as a fixed sand flat.

Tab. 4: Sediment amounts in three BSNE samplers May-August 2006

	Height (cm)	May	June	July	August
		(kg/m²)			
Sampler 1 (in front of aff.)	15.0	272.5	1017.6	1055.4	N/A*
	40.0	120.0	286.5	333.8	238.5
	65.0	97.9	247.2	255.3	77.0
	150.0	48.4	85.2	74.0	29.1
Sampler 2 (center of aff.)	15.0	194.7	460.2	423.1	137.3
	40.0	62.4	228.1	223.6	67.2
	65.0	46.9	154.9	169.5	55.4
	150.0	30.9	115.4	114.7	38.0
Sampler 3 (behind aff.)	15.0	57.1	180.7	148.7	12.5
	40.0	28.6	99.4	118.4	18.1
	65.0	20.6	71.3	91.2	27.0
	150.0	15.2	55.4	76.0	45.0

Since the overall conditions on the three locations can be considered as similar, the factor which causes the decrease in sediment transport can only be the vegetation. This proves the positive effect of the Saxaul afforestation: on the long-term, a well-developed plantation is able to significantly reduce sediment transport and to transform a zone of active transport and erosion into a zone of accumulation and positive sediment balance.

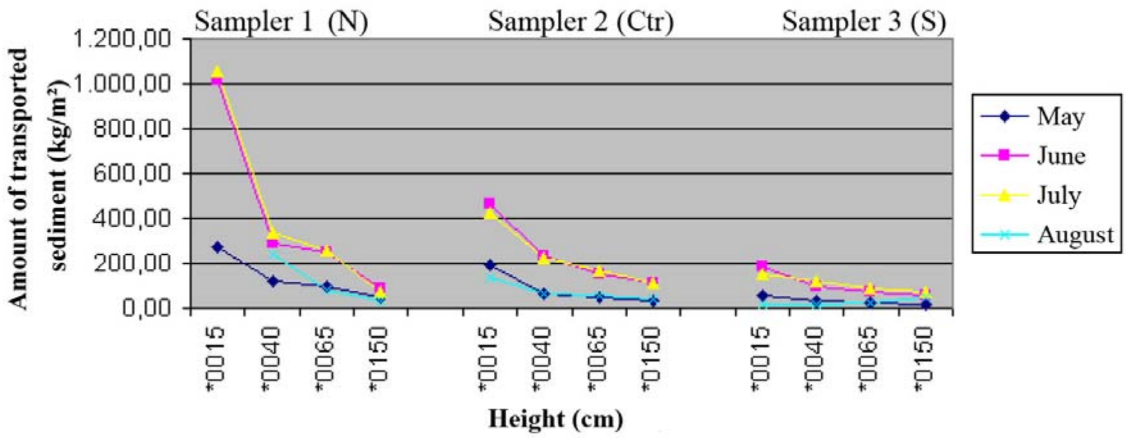


Fig. 8: N-S profile of sediment transport Haloxylon aphyllum afforestation of 2001

Another interesting indicator for the impact of the plantation on sand transport is the fact that the lowest sand trap on sampler 1 was buried in the sand of an approaching dune by August 4th, while the other two samplers remained free of handicaps over the whole measurement period (Mai-November 2006).

Sampler 1
Sand flat with mussels

Sampler 2
Sand flat with mussels and *Aristida karelini*

Fig. 9: Situation of the two BSNE saltation sampler clusters

Apart from the afforestation with *Haloxylon aphyllum*, another technique for moving sand fixation is the sowing of Selin (*Aristida karelini)*, a herbaceous psammophyte with very good sand fixation capabilities. These plants reach a height of up to 1,5m and up to 2m in diameter (including the underlying sand nebkha, which they accumulate over time). Due to its many fine leaves and stems, this plant filters large amounts of sediments out of the air and furthermore fixes the substrate over a large area with its extensive root system. Another very important fact about Selin is its potential use as a fodder plant for livestock. Thus, when an area is sustainably developed with Selin, it can also be taken into a (careful) economic use.

Similar to the experiment described above, the impact of a Selin plantation was assessed in a set-up of two sediment samplers, separated about 800m. Fig. 9 shows the situation of the samplers: Sampler 1 was set-up on a vegetation free sand flat covered with mussels, while sampler 2 was established on the very same sand flat, but featuring a 25% projective cover of *Aristida karelini* with a growth height of approximately 0.8-1m.

Fig. 10 shows the plots of transported sediment for the period June-August 2006. The higher amount of transported sediment over the non-vegetated area is striking, especially right above the surface (15cm). Depending on the measured month, the sediment transport is 93-111 times (15cm), 16-41 times (40cm), 2,2-8 times (65cm) and still 1,7-2,3 times higher (150cm) than on the vegetated area. Even though the most obvious differences are found in the very surface-near layers, the sediment transport in 150cm height and above is also reduced by about 40-55%.

These results underline the aforementioned characteristics of Selin as a formidable “sediment catcher”. This suggests that the use of Selin should be enforced in future phytomelioration activities. However, Selin is a typical psammophyte, and thereby will only grow on sandy substrate with low to moderate salinity. These conditions are typically found on sand sheets and moving sands, i.e. in moderately to highly dynamic landscapes. Therefore, mechanical fixation, like shown in Fig. 11, should be considered before the sowing of *Aristida karelini*, in order to stop the sand from moving and thereby improve the planting success and sustainability of the plantation.

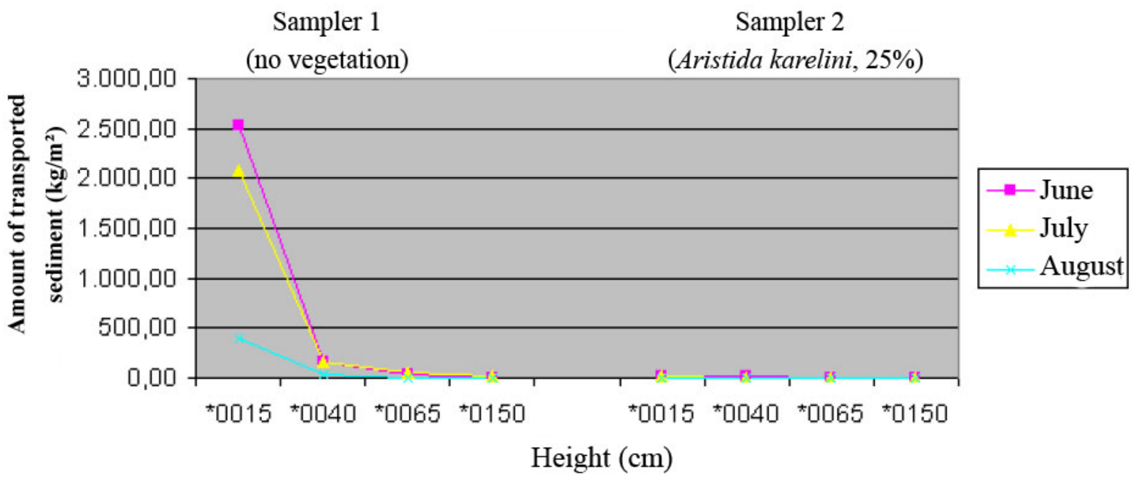


Fig. 10: Sediment transport profiles of a non-vegetated sand flat and a Selin plantation

Fig. 11: Mechanical fixation of moving sand with reed cane

6. Discussion

The results of the remote sensing based forest inventory showed a high heterogeneity of the establishment of the afforestation measures. This fact is highly related to the intensively varying site conditions on the desiccated Aral Sea bed. The suitability of a site for afforestation depends on numerous factors, like groundwater level, soil texture, soil salinity and relief morphology, and needs to be evaluated before a territory is planted. Since these factors vary even on a small spatial scale, the planting techniques should very precisely adjusted to the given conditions, in order achieve a high establishment rate and thereby an economically efficient planting strategy, i.e. consequent and detailed planning is necessary in beforehand. Considering the difficulties of the terrain for the planters as well as the plants themselves, these results indicate that the already respectable growth success rate of 60% can be significantly improved by the use of remote sensing and GIS techniques as a planning instrument.

The high variation concerning the planting direction also underlines the need for an improved planning procedure. Especially the field experts should be equipped with and trained on the use of compasses and GPS systems in order to implement the afforestation plans in the correct manner. Even though this study did not investigate the effect of the planting direction on the effectiveness of the afforestation on wind speed and soil erosion, it can be assumed that wind breaks planted perpendicular to the predominant wind direction have a greater impact than wind parallel ones. In the worst case, wind parallel lines of trees could even accelerate the surface near winds and thereby increase the deflation of sand, dust and salts from the dried sea bed.

The impact assessment of the afforestations on wind speed and soil erosion impressively showed the positive effects of afforestation measures.

Surface near wind speed was significantly reduced by well established lines of *Haloxylon aphyllum* trees and thereby, an effective reduction of sand transport is achieved. It was shown that a highly dynamic landscape can be transformed into a stable by the plantation of “Black Saxaul” trees and thereby act as a very good anti-desertification measure.

Even better sand / soil fixation was achieved by the sowing of Selin *(Aristida karelini).* The sand transport could be reduced by over 90% in the surface near layers and dust transport even in a height of 150cm could be reduced by approximately 50%. However, Selin is a highly specialized *psammophyllous* plant, and can only be planted on sandy surfaces with a low salinity degree. Furthermore, special fixation techniques are necessary to decrease sand movement dynamics in beforehand in order to enable a satisfying establishment rate. The introduction of remote sensing, GIS and GPS-use will be of great importance for a successful phytomelioration with Selin.

7. Conclusions

Stabilizing the desiccated Aral Sea bed through plantation measures is a very difficult task and must be based on sound scientific analysis. From the technical point of view, the GTZ-project proved that is possible to implement large scale afforestation measures on the desiccated sea bed. Availability of information on the site conditions is crucial for successful afforestation measures and must be significantly improved. Due to the remote situation of the territory and the difficult accessibility of the terrain, the combination of remote sensing and GIS techniques with ground based investigations is necessary, as recently proposed by Dukhovny et al. (2008, in press). Based on such data, a scientific impact monitoring should be undertaken, which is indispensable in order to gain further knowledge on the effects of the afforestation measures and to improve the existing planting strategies.

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