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Can early season Landsat images improve locust habitat monitoring in the Amudarya River Delta of Uzbekistan?

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Abstract

Reed (*Phragmites australis*) stands of the Amudarya River delta south of the Aral Sea in Uzbekistan serve as permanent breeding areas of the Asian migratory locust (*Locusta migratoria migratoria*). Locust swarms threaten agricultural fields adjacent to the delta. Every year, specialists from the Uzbekistan Plant Protection Service attempt to survey this vast delta to assess growth of reed which provides a habitat for locust nymphal infestations. Inferences regarding locust distribution are drawn and recommendations for chemical treatments made, based on very limited samples. This often results in blanketing wetland areas with broad-spectrum insecticides, thus harming nontarget fauna. In this study, early season Landsat data, coinciding with the locust survey planning stage, were used to generate a map of potential locust habitat. Using iterative image classification and reference data, a reed distribution map was generated with an overall accuracy of 74% (kappa agreement = 0.686). Landsat data were able to correctly identify 87% of the reed beds, but had some difficulty separating other vegetation when it was mixed with reeds. Minimizing these errors would improve the overall accuracy; however, this does not diminish the utility of this tool for locust habitat monitoring. Incorporation of remotely sensed data into current survey practices could provide precise information about the spatial distribution of reeds. Plant protection specialists could then use this to optimize planning and execution of antilocust treatments, reducing the negative environmental impact of these.

Key words

Amudarya River, Uzbekistan, migratory locust, pest surveys, Landsat, remote sensing

Introduction

Every year thousands of hectares of agricultural fields adjacent to the Amudarya River delta, Uzbekistan, are threatened with defoliation by the Asian Migratory locust (*Locusta migratoria migratoria* L.) (Fig.1). To mitigate this threat, agents of the Uzbekistan Plant Protection Services use (very limited) ground surveys of locust habitat to guide widespread application of broad-spectrum insecticides, a practice often resulting in over-application and environmental damage (Latchininsky & Gapparov 1996). Modern mapping methods using satellite data offer an opportunity to better target surveys and treatments, resulting in more effective control, while minimizing environmental damage. The first step in this process is to generate a habitat suitability map based on the vegetation present at the time of locust nymphal development. Plant protection specialists can obtain information on current vegetation growth and distribution, and design the ground surveys effectively. In the absence of current information, the specialists have to rely on heuristic knowledge of past distributions and the resultant sampling scheme might not match the present vegetation conditions.

Common reeds *Phragmites australis* (Cav.) Trin. *ex* Steud. are the primary habitats for this locust (Novitsky 1963) and are found throughout the delta, either as a monoculture or mixed with other grass species or shrubs. In addition to the reeds, vegetation in the delta includes a forest-shrub mix consisting of several native poplars (*Populus spp.*), elaeagnus (*Elaeagnus spp.*), salt cedar (*Tamarix spp.*), willows (*Salix spp.*) and saxaul species (*Haloxylon spp.*) (Gapparov & Latchininsky 2000). Reeds are opportunistic species growing in moist soils, shallow water bodies, and also in abandoned agricultural fields. Locusts use sandy river banks as oviposition sites, and exploit reed stands for their food and shelter needs during their nymphal and adult stages. Periodic outbreaks occur, during which the locust swarms fly out of the delta to devastate the major agricultural crops of the region: rice, wheat, cotton, melon, and potatoes (Gapparov & Latchininsky 2000). The outbreaks are usually preceded by abnormally dry years when larger areas become free from flooding and expand the habitat suitable for oviposition. Thus after a severe drought in 1945, the Asian migratory locust infested more than 1 million ha in 1946, and chemical treatments to control the plague were implemented on >500,000 ha (Shamuratov & Latchininsky 1991).

During outbreaks, locust hopper bands have extended up to 36 km in the 4th instar, reaching 49 km in the 5th instar; the hoppers climb on one another forming a "moving carpet" of 50-cm thickness (Novitsky 1963). After fledging, the adult swarms disperse in different directions. Tsyplenkov (1970) described one of the longest migrations of *L. m. migratoria* from the Amudarya delta, in which a swarm flew westwards, crossed the Caspian Sea and landed in Azerbaijan (Transcaucasia), covering a distance of >1000 km. According to Novitsky (1963), the size of a landed swarm could reach 120 by 10 km (120,000 ha). Adult density in such swarms is 10 to 50 individuals per m^2, but frequently reaches 2000 to 3000 per m^2 in the oviposition sites. The average egg-pod density is about 5 per m^2, with a maximum of 140 per m^2. Each female lays three to four egg-pods containing 32 to 120 eggs, the average ranging from 60 to 80 eggs (Shamuratov & Latchininsky 1991). The locusts become extremely voracious during sexual maturation and mating, destroying all available vegetation down to the soil level. Poplars and willows in the fluvial forests often collapse under the enormous weight of the landed swarms. Thousands of hectares of irrigated cotton, small grain and vegetable crops, are frequently destroyed.

In the Amudarya delta, the Asian Migratory locust exhibits a univoltine life cycle with embryonic diapause (Gapparov & Latchininsky 2000). The annual locust surveys are conducted during mid-May through early June to coincide with locust hatching and the appearance of early nymphal stages. Results from these surveys

are used for characterizing the risks of habitat susceptibility to locust infestation, and for planning insecticide control operations. Subsequently, the reed stands with high risk of locust infestations are treated with pyrethroid and organophosphate insecticides, which are applied primarily as aerial sprays. The goal of the locust management program in the Amudarya delta is to treat nymphal bands in order to prevent swarm migration into the adjacent agricultural fields.

The locust surveys however, are conducted on only a small portion of the delta, due to lack of resources such as automobiles and personnel, along with the limitations associated with insufficient infrastructure (roads). Most of the delta is inaccessible and specialists must rely on rowboats to survey certain remote areas. Under the best access circumstances, a professional scout can inspect between 100 and 150 ha daily during the survey period (Tsyplenkov 1970). This means that for a team of 20 locust scouts working in the delta, it would take 11 to 16 mo to complete a survey. In reality, the survey should be accomplished in just 3 to 4 wk, before the majority of the insects reach the adult stage and escape control. In accord with current practices, in any given year only a portion of the delta is surveyed and, based on these limited results, inferences are made for the entire delta. This leads to decision-making based largely on heuristic knowledge about past locust distributions. Specialists often visit the same sites year after year, and inferences for locust management are drawn without a comprehensive spatial characterization of reed distribution within the delta.

Based on the subjective risk estimates, thousands of hectares are treated with broad-spectrum insecticides with dire consequences for nontarget organisms in the fragile delta ecosystem (Latchininsky & Gapparov 1996). At the same time locust infestations in many undersurveyed areas often remain untreated, which leads to swarm formation. The swarms are known to create havoc not only in the adjacent crop areas, but in those situated far from the delta.

Fig. 1. Above, adult Asian migratory locust. Photo by A. V. Latchininsky & S.P. Schell, University of Wyoming. B. Right, hopper band of 5th instar nymphs of LMI. Photo by A.V. Latchininsky. See also PLATE IV.

In order to select representative survey sites and reliably estimate locust infestation risk, satellite-based remotely sensed data could be used to characterize the reed distribution. Moderate resolution satellites such as Landsat have a demonstrated utility for mapping vegetation types that could serve as locust habitats (McCulloch & Hunter 1983, Bryceson & Wright 1986, Bryceson 1989, Bryceson 1990, Sivanpillai *et al*. 2006). Satellite data could be used to identify the extent of reed growth in the delta, and this information used to devise optimal locust monitoring strategies. Inferences drawn from such survey schemes would enable the plant protection specialists to devise adequate insecticide treatment plans, where chemical applications could be targeted to pest infestations, instead of the current blanket application practices. Since satellites collect such data on a periodic basis, this methodology could be applied every year and sampling bias, which arises from visiting the same set of sites every year, could be minimized.

The primary objective of this study was to test the utility of an early season (mid-May) Landsat-Enhanced Thematic Mapper Plus (ETM+) image for identifying and mapping reed beds in the Amudarya Delta. The secondary objective was to estimate the area of the reeds, both in monoculture and mixed with other vegetation types, and to develop a locust-risk map based on the degree of suitability for locust habitats.

Materials and methods

Study area.—The Amudarya River delta extends over an area of 1.4 million ha south of the Aral Sea and consists of numerous channels, ponds, lakes, large and small rivulets and islands. For this study, an area representing 2 million ha that included the northern portion of the delta and adjoining sandy areas, as well as the southern portion of the Aral Sea, was selected (Fig. 2). The northwest corner of the study site (lat 44° 18'N, long 58° 8'E,) was at the confluence of the delta with the western boundary of the Aral Sea, and the southeast corner of the study site (lat 43° 11'N, long 60° 21'E) included the desert east of delta.

Satellite data.— Two ETM+ scenes (Path 161, rows 29 and 30) acquired on May 16, 2002, were selected for this study. At about this time of year, the plant protection specialists start their field surveys. ETM+ scenes consist of three visible and three infrared image bands, with a spatial resolution of 30 m. These scenes were rectified and georeferenced to the UTM projection (zone 40) and the WGS84 spheroid at the US Geological Survey (USGS) Earth Resource Observation and Science (EROS) Center at Sioux Falls, SD (USA). ETM+ bands were imported into ERDAS Imagine software v 8.4 (Leica Geosystems, Atlanta, GA) and a subset corresponding to the study area (2,073,324 ha) was extracted from the larger image.

Reference and verification data.—Reference and verification data were collected through interviews and field visits, respectively. Plant protection specialists were interviewed to gain insights about reed growth and distribution within the delta. Locations with reed monoculture and combinations of reed and other vegetation were identified. Local experts identified several abandoned agricultural fields invaded by reeds, and distinguished them from active agricultural fields. Through this method, 76 reference points were collected to aid image classification.

Verification data were collected through field and aerial surveys conducted in June 2004. Sites that were accessible were surveyed from roads, whereas remote locations were surveyed aerially. A Garmin (Garmin Ltd., Olathe, Kansas, USA) Global Positioning System (GPS) receiver was used to record the geographic coordinates of the sites. Plant protection specialists, and in a few cases farmers, were consulted about the condition of each site and changes since 2002. Detailed descriptions of the vegetation composition and photos were taken for each site. Through this process, 203 verification data points were obtained, but only 163 of them were within the present study area.

Image classification.—Pixels in the ETM+ image were assigned to thematic (land-cover) classes using an iterative, unsupervised image classification technique (Driese *et al*. 2001, Wymann *et al.* 2001, Driese *et al*. 2004, Sivanpillai *et al*. 2005). This methodology minimizes the overall variance in the original data and maximizes the distinction between various land-cover classes (Wymann *et al.* 2001). Analysts can identify and label land-cover classes iteratively until all the classes are identified. During each iteration (or step), pixels in the image were classified to generate some number (a) of clusters and, with the aid of reference data, a subset of these clusters assigned to land-cover classes. Pixels corresponding to the labeled clusters were removed from the original image and the remaining pixels classified to produce a new classified image with (b) number of clusters. With the aid of reference data, some of these clusters were assigned to land-cover classes. In the third step, pixels from these labeled clusters were removed and the remaining pixels classified again to generate new clusters, thus resulting in fewer and fewer unclassified pixels in each step. This classification and labeling process was repeated until all the pixels in the original image were assigned to land-cover classes. At the end, a single composite image was generated by combining all the land-cover classes identified in each step.

Accuracy assessment and area estimation.—Verification data (n=163) were used to assess the accuracy of the classified image. An error matrix was generated by comparing the agreement between each verification site and the corresponding thematic class from the classified image (Congalton 1991, Jensen 2004). Overall accuracy, producer and user accuracies for each thematic class, were calculated. Overall accuracy conveys the agreement between classified satellite image and verification data. Producer accuracy is a measure of success in classifying each thematic class and reflects the mapmaker's ability to differentiate various classes on the ground. User accuracy is a measure of usefulness from the map user's perspective and represents the probability of finding the same thematic class on the ground that is portrayed in the map. The Kappa statistic was computed for the classified image and conditional kappa statistics were computed for each thematic class. The Kappa statistic is a single metric (1.0 indicates total agreement) that incorporates both producer and user accuracies and facilitates easy comparison of classification accuracy (Congalton 1991). Area estimates for each thematic class were derived from the classified imagery.

Results

Image classification.—Pixels were assigned to thematic classes (Table 1) using the iterative classification procedure described in the previous section. In the first iteration, pixels in the ETM+ image were grouped into 150 clusters. Clusters corresponding to water, sandy soils and sparse vegetation types were identified, using reference data, field notes and photographs. Pixels included in these labeled clusters were removed and set aside and in the second iteration the

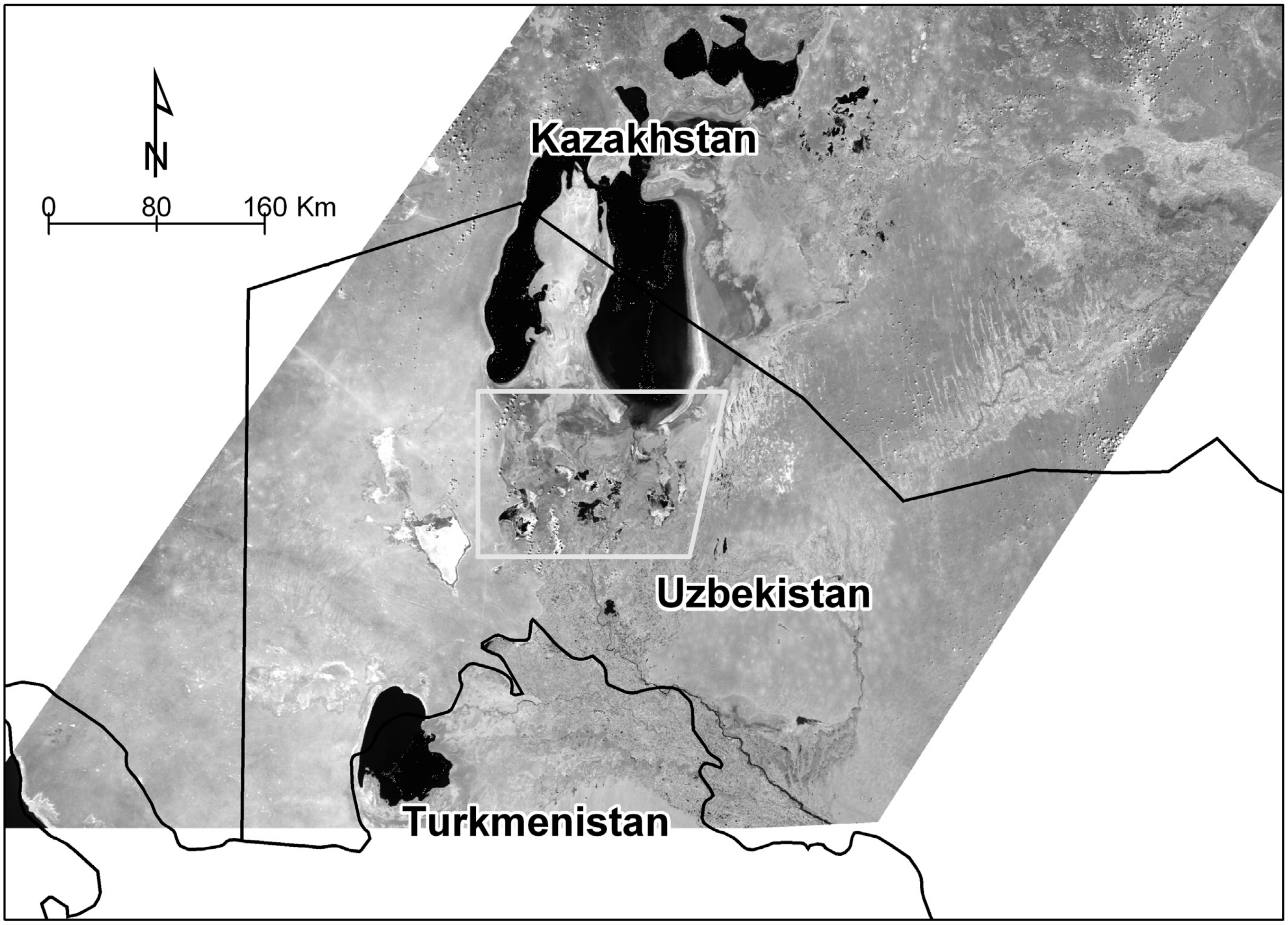


Fig. 2. Amudarya River delta (Uzbekistan) and the Aral Sea. Highlighted area corresponds to the location of the study area.

remaining pixels in the ETM+ image, corresponding to various vegetation types, were reclassified to generate 100 new clusters. Each of these clusters was assigned to reeds (class 1), reeds/other vegetation mix (class 2), other vegetation (class 3) and sparse vegetation (class 4), using reference notes and photos to aid in cluster labeling. At the end of second iteration, classes identified from both iterations were combined to create a single land-cover map of the entire study area (Fig. 3).

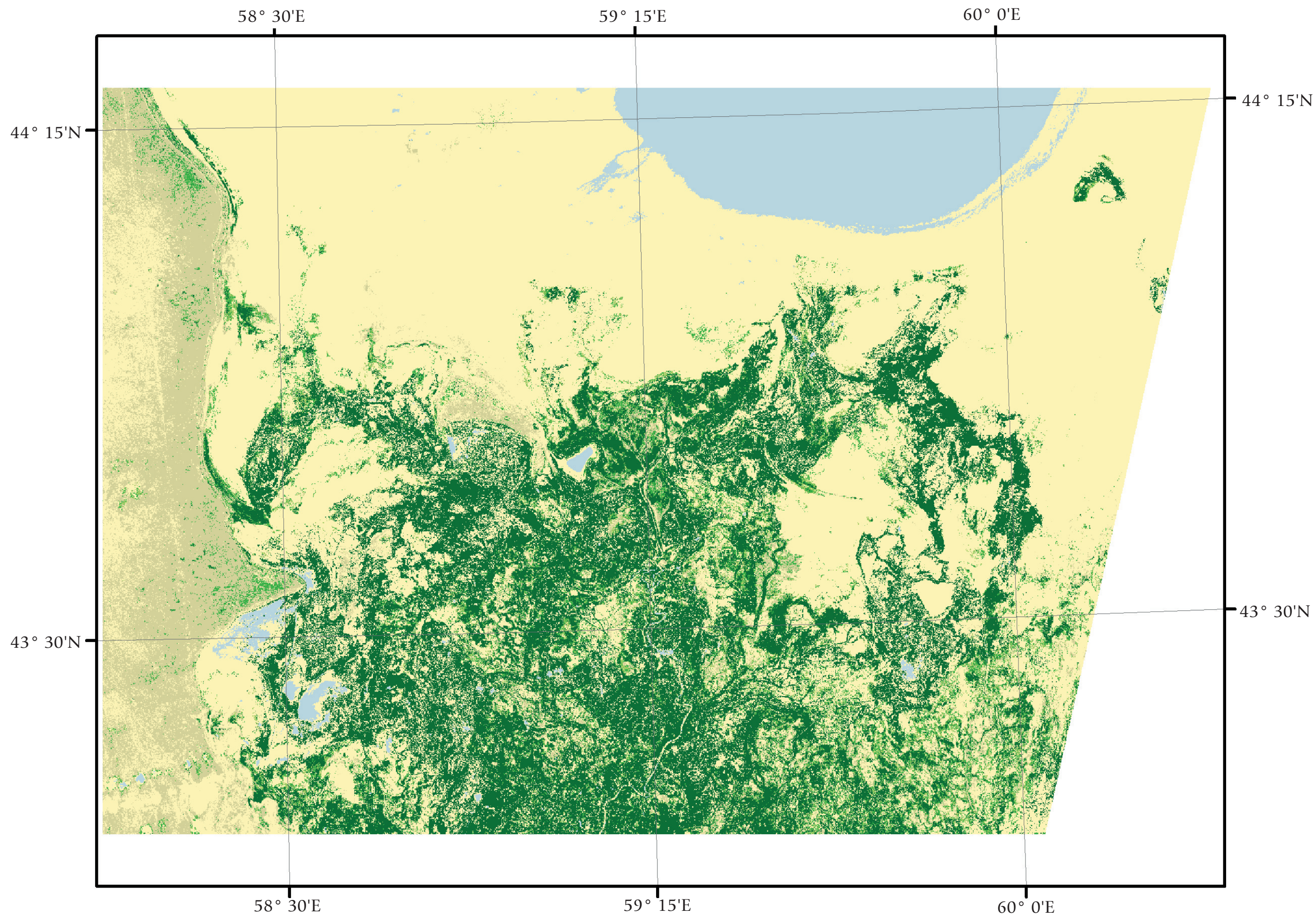
Based on comparison of reed spectral values from the imagery with those of other vegetation types, reeds were spectrally distinct from other classes. Spectral reflectance for the reeds/other vegetation mix class (class 2) was lower than that of pure reeds (class 1). Areas with sparse vegetation had some spectral overlap with sandy soils.

Classification accuracy and area estimation.—The overall accuracy of the classified image was 74%, based on comparison of classified pixels to 163 verification sites (Kappa = 0.686) (Table 2). Two major sources of error were: 1) misclassification of "other vegetation" (class 3) as "reed/other vegetation mix" (class 2), and 2) misclassification of reed/other vegetation mix as reeds (class 1). Fourteen out of the 40 (35%) "other vegetation" (class 3) verification points were misclassified as either reeds or "reed/other vegetation mix", resulting in a producer's accuracy for this class of 58% (Table 3). Also, 5 out of 21 (24%) "reed/other vegetation mix" sites were misclassified as reeds. From these results it is evident that we were not able to consistently separate the "other vegetation" class from reeds or the "reeds/other vegetation mix" class (class 2), or class 2 from reeds, resulting in some confusion between these classes in the final map. Misclassification of water bodies (class 6) as sandy soil (class 5) was another significant source of classification error and the producer accuracy for water was only 57% (Table 3).

Table 1. The land cover classification used for mapping potential locust habitats. Classes were grouped based on their potential risk as a locust habitat.

Class name and description	Locust habitat risk
1. Reeds (reeds monoculture)	High
2. Reeds/other vegetation mix	Medium
3. Other vegetation with very few reeds	Medium/low
4. Sparse vegetation (shrubs and other vegetation)	Low
5. Sandy Soil	Low
6. Water (shallow lakes, rivers and Aral Sea)	Low

We were able to correctly classify reeds at 26 of 30 locations (producer accuracy = 87%) (Table 3) and most of the reed verification sites were correctly classified (user accuracy = 74%). At misclassified locations on the map, users will mostly likely find "a reed/other vegetation mix" or "other vegetation" at the corresponding location



Map Classes	Area in hectares (proportion)	Risk of locust infestation
Reeds	441,255 (21%)	High
Reeds & other vegetation	89,192 (4%)	Medium
Other vegetation	54,602 (3%)	Medium/low
Sparse vegetation	188,265 (9%)	Low
Sandy soil	1,153,709 (56%)	Low
Water	146,331 (7%)	Low

Fig. 3. Classified Landsat image depicting the spatial distribution of reed beds in the Amudarya River delta and adjoining areas. These reed beds have the highest risk as potential habitats of the Asian migratory locust. See also PLATE V.

on the ground. Our assessment also indicated that we were able to correctly classify sandy soil (producer accuracy = 94%), but that we misclassified sparse vegetation (producer accuracy = 68%) and confused water (producer accuracy = 57%) with sandy soil, lowering the user accuracy of the sandy soil class to 66%. Since these latter three classes (4 through 6) do not pose substantial risk for becoming locust habitat, further refinement of these classes is not important from a locust manager's standpoint.

Reeds occupied 21% (441,255 ha) of the total area mapped in this study (Table 3) and reed stands constitute a high risk of potential locust habitat. In 4% (89,192 ha) of the total area, reeds were found mixed with other vegetation (class 2). These areas correspond to medium risk of potential locust habitat. Together, reeds and reed/other vegetation mixtures occupy approximately a quarter of the study area (530,447 ha) and represent either high or medium risk as potential locust habitat.

The "other vegetation class" (class 3) constituted only 3% (54,602 ha) of the study area and sparse vegetation occupied 9% (188,265

Table 2. Error matrix generated for the classified Landsat image. Image data are in columns and ground verification data are in rows. Diagonal elements (in bold) represent the agreement and off-diagonal elements represent the disagreement between the classified image and verification data.

Classes	1	2	3	4	5	6	Total
1	**26**	1	0	1	2	0	30
2	5	**16**	0	0	0	0	21
3	3	11	**23**	0	3	0	40
4	0	1	1	**17**	5	1	25
5	1	0	0	0	**31**	0	33
6	0	1	0	0	6	**8**	14
Total	35	30	24	18	47	9	**163**

Overall accuracy = 74%
Kappa agreement index = 0.686
Class numbers refer to the six thematic classes listed in Table 1

ha). A major portion (56%; 1,153,709 ha) of the study area was sandy soil, while water bodies were found in 7% (146,331 ha) of the area.

Discussion

Using a single ETM+ image acquired in early season (mid-May), we were able to distinguish a majority of the reed beds in the study area. Reeds had higher spectral reflectance in near- (band 4) and mid- (band 5) infrared bands than other grasses, shrubs and trees, resulting in successful separation. The ETM+ imagery also allowed us to distinguish the reeds growing in abandoned agricultural fields from those growing in wet soils along river channels, lakes and dried lake beds. It also captured several small, narrow patches of reeds along channels in the study area, suggesting that the spatial resolution of ETM+ pixels (30 m) is adequate to capture small patches of reeds which represent potential locust habitat.

When other vegetation was mixed with reeds (class 2), the spectral reflectance decreased in bands 2 (green), 4 (near infrared) and 5 (middle infrared), in comparison to those locations that contained mostly reeds (class 1). Early in the growing season grasses and sedges, which often created a mixed stand with reeds, might not have greened up yet, and this could have resulted in the lower reflectance values in these bands for class 2. However the spectral overlap witnessed in classes 1, 2 and 3 and quantified in the error matrix (Table 2), indicates that vegetation might occur as a gradient starting from mostly reeds and transitioning to mostly other vegetation, onto which we have imposed artificial spectral breaks. Another source of classification error was confusion between classes 5 (sandy soil) and 6 (water). This error could be due to fluctuations in the water level in the lakes and small ponds causing a mismatch in timing between field verification and image data. Since some of the verification points were taken away from the center of the water bodies, it is possible that those points did not contain any water in early May when the ETM+ image was acquired. Nevertheless, because water bodies have a very low probability of becoming locust habitat, this classification error does not significantly affect the utility of the classified image for its primary purpose, conducting locust surveys.

Based on the results, about 25% of the mapped area can be categorized as at either high or medium risk for becoming locust habitat. The misclassification of the reed/other vegetation mix class

Table 3. Producer accuracy and user accuracy values and area occupied by each land cover class in the classified Landsat data.

Land cover classes	Producer Accuracy	User Accuracy
1. Reeds	87%	74%
2. Reeds & other vegetation	76%	53%
3. Other vegetation	58%	96%
4. Sparse vegetation	68%	94%
5. Sandy Soil	94%	66%
6. Water	57%	89%

(class 2) and the other vegetation class (class 3) as reeds (class 1), may result in over-prediction of the reed area. "Commission" (addition of a type to the map that is not present on the ground) is a common problem in reed classification using satellite imagery (Sivanpillai *et al.* 2006, Sivanpillai & Latchininsky 2007), but is less critical than "omission" for locust habitat monitoring. More importantly, the satellite data provide the locust control specialists with spatially distributed, timely information on reed distribution, allowing them to optimize ground surveys and subsequent insecticide treatments. Even with map error, this is a significant improvement over the current system.

Current practices restrict ground surveys to accessible areas along a few existing roads on the river delta. As a result, only a tiny proportion of the reed stands is actually surveyed. A simple GIS analysis showed that if these ground survey points are located within a 1000-m buffer along the existing roads (which is probably an overestimation), the buffers will include < 8% (33,974 ha) of the total area of reeds in the study zone (441,255 ha). This means that currently, decision making regarding locust monitoring and management is based on grossly insufficient and almost certainly nonrepresentative data.

Timely and accurate information about the spatial distribution of reeds within the Amudarya River delta could assist the plant protection specialists in several ways. A map depicting reed distribution could aid in the allocation of resources and personnel for a more efficient ground survey. Sampling sites could be redistributed to reflect the existing reed distribution and ensure adequate coverage of the delta. Furthermore, locust habitat maps could provide a valuable indication of the potential locust threat from neighboring zones. Locust swarms do not recognize administrative boundaries and spatial knowledge of areas adjacent to managed zones would be a big improvement over spatially isolated and nonrepresentative sampling. Not only would such information allow better anticipation of locust invasions, but it would facilitate preemptive preparation of contingency plans to reduce damage when such invasions do occur. Accurate habitat maps will also be useful for guiding insecticide treatments, by concentrating the applications on areas with high risk of locust infestation, while avoiding areas where treatments are most likely to cause environmental degradation. In particular, this will result in minimizing chemical treatments in the immediate vicinity of the numerous water bodies in the delta. Locust habitat maps derived from satellite images will not necessarily result in the reduction of treated acreage; rather, they will help to redistribute the treatments within the delta according to the risk of locust infestation. Current practices of almost "blind" blanketing of wetlands with chemicals will give way to targeted, scientifically-based treatments, reducing environmental pollution.

Using Landsat or similar medium-resolution data will allow reed distribution maps to be produced every year. Regular mapping across time allows adjustments to be made to the number and location of sites visited on an annual basis. Late-season egg-pod surveys can also be optimized using satellite information to locate sandy areas suitable for locust oviposition. Furthermore, multiyear information can be used to gain insights about annual changes in reed distribution. Such knowledge would enable the plant protection specialists in Uzbekistan and other similar areas to identify places that have high reed distributions every year, versus those that experience increases only rarely or never.

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