

Can late summer Landsat data be used for locating Asian migratory locust, *Locusta migratoria migratoria*, oviposition sites in the Amudarya River delta, Uzbekistan?

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Abstract

Existing survey methods for assessing the Asian migratory locust, *Locusta migratoria migratoria* L. (Orthoptera: Acrididae), infestation risk in the Amudarya River delta, Uzbekistan, are largely constrained by economic resources and site accessibility. The surveys are restricted to a few easily accessible areas, which leads to a misinterpretation of the threat of locust infestation. This often results in indiscriminate blanket treatments of vast areas of wetlands with broad-spectrum insecticides, which may adversely impact non-target fauna and flora. In order to minimize the bias during surveys, one approach would be to allocate the sampling locations based on the distribution of the primary food and shelter plant of the locusts, the common reed, *Phragmites australis* (Cav.) Trin. ex Steud (Poaceae). In this study, we evaluated the utility of satellite-based remotely sensed data (Landsat TM) acquired in August 2006 to characterize reed distribution in the delta and identify potential locust oviposition sites. The overall accuracy of the Landsat data to map land cover classes in the delta was 84%. The Landsat TM data identified 90% of the reeds, but it was less useful in identifying areas where other vegetations (shrubs and grasses) were mixed with reeds. During the following summer field survey in June 2007, we identified 37 sites that were infested with early-instar locusts. The low migration capacity of young nymphs in dense reed vegetation allowed us to presume that these sites were used for oviposition in the previous summer. Twenty-eight (74%) of these 37 sites had reeds in the previous year. Results from these studies demonstrate that reed distribution maps derived from satellite data could be used for targeting locust egg-pod survey locations, in order to minimize sampling bias while predicting locust infestation risks for the following season.

Introduction

Ground surveys are an integral part of the Asian migratory locust (AML), *Locusta migratoria migratoria* L. (Orthoptera: Acrididae), management strategy in its permanent breeding area in the Amudarya River delta, Aral Sea basin, Uzbekistan. The AML exhibits a univoltine life cycle in the wetland delta (Novitsky, 1963). Egg-laying occurs in late summer (late July–August). Females oviposit into

sandy soil within and adjacent to dense stands of the common reed, *Phragmites australis* (Cav.) Trin. ex Steud. (Poaceae), which represents the main component of the wetland vegetative cover. Eggs undergo obligatory embryonic diapause during winter and hatch the following spring in late May (Latchininsky & Gapparov, 1996). Nymphs feed on reeds during their five-instar developmental period, which takes 5–7 weeks. The reed resource often becomes depleted by the time of adult emergence (mid-July). In search for food, fledged locusts then start to produce emigration flights from the wetlands into adjacent croplands. Their impending economic damage to wheat, barley, melons, vegetables, and other crops requires large-scale chemical treatments of source reed habitats. In

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the Amudarya delta, which covers an area of >1 million ha, such treated areas frequently exceed several 100 000 ha a year (Gapparov & Latchininsky, 2000).

Specialized locust control personnel conduct the first survey in August/September to assess the spatial distribution and density of locust egg-beds. Results of this survey are used to forecast the risk of locust infestation the following year. In the spring (mid-April to early May), the second survey is conducted to determine the overwintering survival rate of the embryos and reassess the locust infestation risk. Based on these surveys, the egg-pod infested areas are identified and delineated. After mass hatching of nymphs (typically in late May), chemical treatments are applied to these areas in order to prevent swarm formation and crop damage (Latchininsky et al., 2002).

However, due to access and resource limitations, surveys are conducted only in a few easily accessible locations, thus biasing the estimates of the locust infestation risk. This often results in indiscriminate, blanket treatments of vast areas of wetlands with broad-spectrum insecticides, which aggravate the ecological catastrophe of the dying Aral Sea (Stone, 1999). On the other hand, poorly surveyed remote areas may produce swarms that remain uncontrolled. These could fly out of the delta later in the season and jeopardize crops. Such swarm emigrations would require emergency treatments, which further increases pesticide load in the wetland ecosystem. As a result, multiple treatments are often applied to the same areas. In order to reduce such adverse effects to the environment, anti-locust treatments should be well-targeted, timely, and effective, aiming at early nymphal stages.

The first step in this direction would be to implement efficient locust surveys, resulting in a realistic forecast. As the life cycle of *L. migratoria migratoria* is well-synchronized with the phenology of its primary food plant, *P. australis* (Tsyplenkov, 1970), the surveys must address the spatio-temporal extent of reed growth. In 2004, a wet season following unusually high snowmelt, the Amudarya delta was flooded, and almost 20 000 ha of new reed growth appeared in the dried Aral Sea bottom (K Djemuratov, pers. comm.). These large expanses of newly established reed beds were 60–80 km north of the limit of the sites routinely surveyed by the locust scouts, so no control was applied. These reed beds served as suitable oviposition sites and in the following spring large locust swarms were recorded in the delta. As a result, the infested areas more than doubled from 46 000 ha (2004) to 95 460 ha (2005) (K Djemuratov, pers. comm.). In this context, information about the distribution of reeds during late summer (August) would provide insights about potential oviposition sites within or adjacent to the reed stands. Using this information, the locust control personnel could redistribute the survey

points within the delta to minimize over- and under-estimation of the locust risk, and get away from the current practice of relying on heuristic knowledge and surveying the same, limited locations year after year.

One approach to improving the efficiency of these ground surveys is to incorporate remotely sensed data collected by earth-orbiting satellites. Information derived from satellite-based remotely sensed data could be used to map reed distribution within the delta, and this could form the basis for redistributing the survey sites. Although several satellites collect various types of data, the medium resolution data (between 20 and 120 m) collected by Landsat (USA), SPOT (France), and IRS (India) appear to provide adequate detail to map reed beds in the delta. Coarser resolution data (>120 m) such as Moderate Resolution Imaging Spectrometer (MODIS) are available at no cost, but do not provide adequate spatial detail to map numerous small patches of reeds in the delta (Sivanpillai & Latchininsky, 2007). Landsat data (at 30 m resolution) are widely used for mapping vegetation and other earth surface features (Lillesand et al., 2004; Campbell, 2006). Furthermore, from the six Landsat reflectance bands, several vegetation indices can be derived and associated with plant vigor or photosynthetic activity of the vegetation. Repeat acquisition (every 16 days) allows periodic monitoring of changes occurring at any location on the surface of the earth. Sivanpillai et al. (2006) mapped the reed distribution pertaining to AML habitats in the River Ili delta, Kazakhstan, using Landsat data. Reeds had relatively higher reflectance values than other vegetation in delta, which enabled their successful identification in the Landsat image. Using a similar technique, Latchininsky et al. (2007) demonstrated the utility of Landsat data for mapping emerging reeds early in the growing season (May) to coincide with the hatching of *L. migratoria migratoria* eggs.

Landsat images acquired in mid- to late August would be useful to quantify the extent of reed distribution and thus provide insights about the potential area available for the AML to lay their eggs. This means that the risk of locust infestation in the following year could be assessed using the images acquired in the preceding year. In order to minimize the errors associated with the identification of reeds, Landsat images must be acquired following the senescence of agricultural crops. If reed growth is adversely impacted due to drought or other weather-related factors, this would translate into less area available for the AML to lay their eggs. In certain years, however, when the adult locust population density is very high, the gravid females become less selective for egg-laying substrate (Uvarov, 1977) and the type and quality of the habitat may not be the predominant criterion for choosing oviposition sites. Barring such rare exceptions, information derived from

Landsat about reed growth and extent appears to be a useful predictor of the potential locust egg-laying sites.

One approach to verify the efficacy of the mid-August Landsat land cover classification results is to compare them with the locust nymph distribution in the following year (June). If any association can be established between the locust nymph distribution and the preceding year's vegetation type at that site, it will enable the locust control personnel to better focus their survey and treatment efforts.

Objectives of this study were: (i) to map the overall vegetation and other land cover type (e.g., bare ground and water) distribution and to estimate the area of each type using raw and derived Landsat data acquired in August 2006, and (ii) to test the relationship between the sites that had locust nymphs in June 2007 and the corresponding vegetation condition in August 2006.

Materials and methods

Study area

The Amudarya River delta occupies 1.4 million ha of wetlands south of the Aral Sea. It includes numerous channels, lakes, rivers, and islands. The predominant vegetation consists of reed (*P. australis*) stands. Other plant communities include shrubs (*Tamarix* spp. and *Salix* spp.) that may be mixed with reeds or stand alone. The southern part of the delta harbors irrigated crop fields of rice, cotton, small grains, and vegetables. The study area was distributed within the 44°19'N, 58°08'E (upper left) and 43°10'N, 60°22'E (lower right) geographic coordinates, and included sand beds adjacent to the Amudarya River delta and the southern extent of the Aral Sea (Figure 1). This resulted in a study area of approximately 2 million ha.

Landsat data

The study area was included in two Landsat scenes (WRS2 path 161, rows 29 and 30). These cloud-free scenes were acquired on 7 August 2006 and rectified to UTM (zone 40) and WGS 84 datum (unit meters) and obtained in tagged image format (TIF). Most of the agricultural crops had been harvested, thus the chances for misclassification of agricultural crops as natural vegetation should have been

minimal. Six multi-spectral bands from both images were imported to ERDAS Imagine (Leica Geosystems, Atlanta, GA, USA) PC version 9.1 and subsets corresponding to the study area were created. Using image mosaic tools, these two subscenes were merged to create a single image covering the entire study area, and used for subsequent processing and classification.

Verification data

The accuracy of the classified Landsat image was assessed using 155 verification points. Of these, 142 verification data points were collected in June 2007 by four field and two aerial surveys. Points representing the five land cover classes (Table 1) were collected and their geographic location was recorded with a Magellan Global Positioning System (Magellan Navigation, Santa Clara, CA, USA) receiver. Additionally, 13 verification data corresponding to water bodies were identified on the map. These water bodies were distributed throughout the study area.

Locust data

During the ground field surveys on 15–17 June 2007, 38 locations with the presence of locust nymphs were recorded using the GPS receiver. Nymphal density was assessed visually by counting insects on 10 1-m² plots at each location. Average instar of the nymphs in bands was calculated from sampling 100 nymphs at each location using a standard entomological sweep net with a 0.3 m ring diameter. Same samples were also used to assess phenotypic phase attributes of the nymphs based on the criteria developed by Bei-Bienko & Mistschenko (1951) and modified by Tsyplenkov (1970).

Image processing

Landsat pixels were iteratively classified to clusters using an unsupervised classification (ISODATA) algorithm in ERDAS Imagine. In the first iteration, certain clusters were assigned to a map (or land cover) class and were removed from the original image. In the next iteration, additional land cover classes were identified from the clusters generated from the classification. Pixels corresponding to these clusters were removed. This process was repeated

Table 1 Land cover (or map) classes identified from the 7 August 2006 Landsat image

Class	Name and description
1	Reeds (locations that contain entirely reeds or reed monoculture)
2	Reeds and other vegetation (locations with mostly reeds but contain other vegetation as well)
3	Other vegetation with some reeds (locations with mostly shrubs and few reeds)
4	Sandy soil and sparse vegetation (sandy soil sites with no or sparse/dried out vegetation)
5	Water (includes all water bodies)

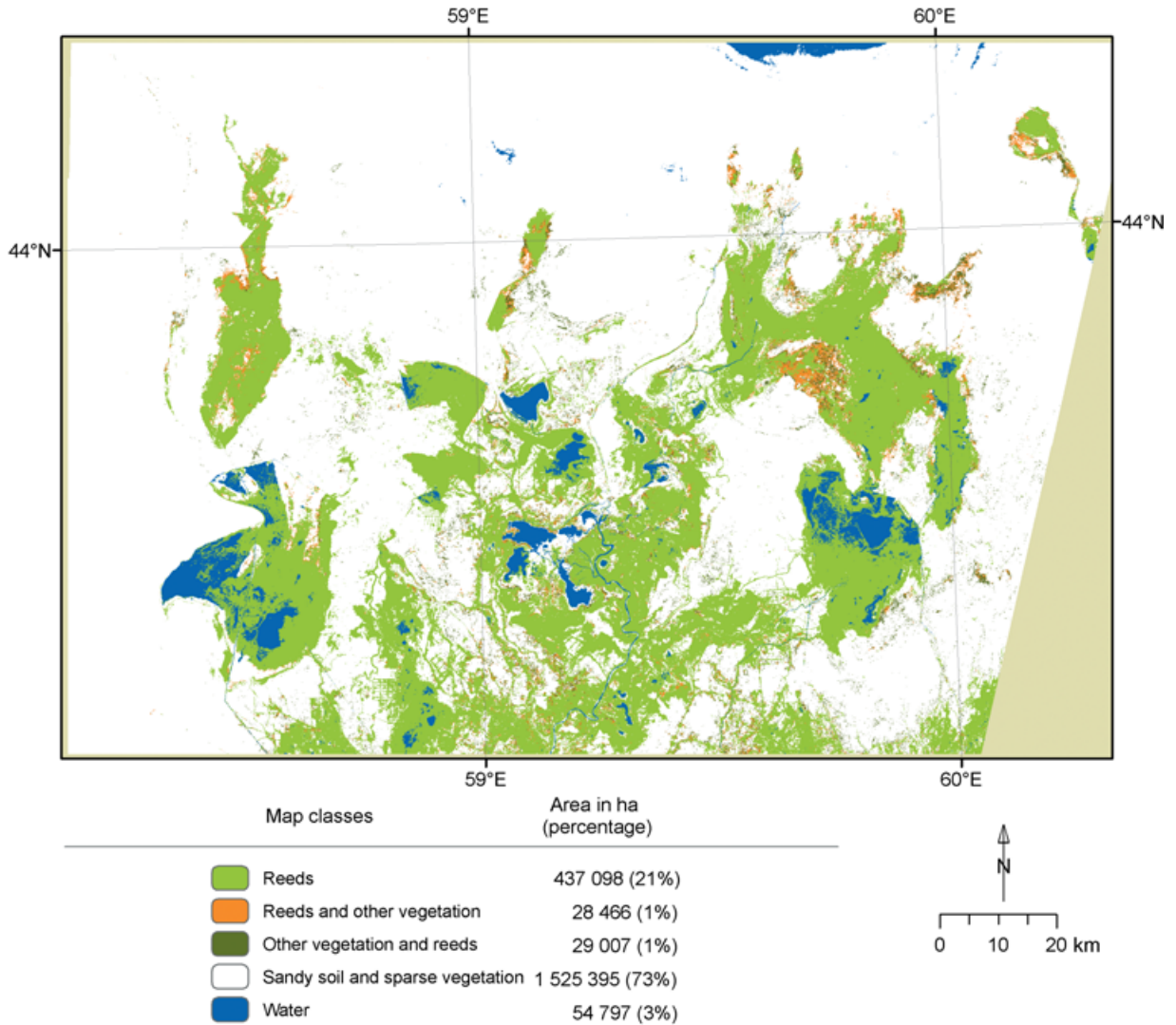


Figure 1 Land cover map of the Amudarya River delta (Uzbekistan) derived from the Landsat imagery and the area of reeds and other land cover classes.

until the pixels in the entire image were assigned to a certain land cover class. A major advantage of the unsupervised classification algorithm is that it does not need a priori knowledge of all the land types along with their variations for image classification (Wilkie & Finn, 1996). Analysts could use previously collected reference points to assign the pixels to various map classes, rather than collecting new field data. Iterative classification algorithm separates different land cover types based on their reflectance values and is ideally suited to separate subtle differences among the same land cover features (Jensen, 2000). This allows the analyst to partition the overall variability in the Landsat image and separate each land cover class in the study area. This technique was successfully employed by Wayman

et al. (2001), Driese et al. (2001), and Sivanpillai et al. (2005) to map different forest types, and Sivanpillai et al. (2006) and Latchinsky et al. (2007) to map reed beds in Central Asia. Field data collected in 2004 (Latchinsky et al., 2007) were used to assign the clusters generated in each iteration to one of the map or land cover classes in Table 1.

Accuracy assessment

Land cover accuracy of the classified Landsat image was computed using the 155 verification data points (Campbell, 2006). A verification point was determined to be correctly classified if the land cover class observed on the ground matched with the land cover class identified by the Landsat

image (Hudson & Ramm, 1987). Results from the accuracy assessment are reported in the form of an error matrix (Congalton, 1991; Jensen, 2000), and from this error matrix the overall classification and individual class accuracies, omission and commission errors can be computed. Omission error reports the number of instances (in percent) when the image analyst failed to correctly identify a land cover feature, whereas the commission error reports the number of instances (in percent) when the image analyst incorrectly identified a land cover feature. Using these error matrices, a κ agreement index value was computed, which reports the agreement between the ground observed and image-derived data. These error matrices are useful while determining the utility of the classified Landsat image for various applications.

Locust nymph presence and vegetation type

The relationship between the locust presence (in 2007) and vegetation type (in 2006) was analyzed by overlaying the AML distribution data with the land cover type from the classified Landsat image. Geographic location was incorrectly recorded in one of the 38 AML locations, hence it was removed from subsequent analyses. At each site, the vegetation or land cover type was determined for an area corresponding to 15×15 pixels (i.e., 20.25 ha) centered at the location where the locust nymphs were found. A large 'spatial window' of 450×450 m was chosen to ensure that since hatching and by the time of the survey (15–17 June), the locust nymphs remained within this area.

Results

Image classification

Two iterations of image classification were required to map the five land cover classes in the Amudarya River delta. In the first iteration, pixels in the Landsat image were classified and assigned to 100 clusters. Using the reference data and reflectance pattern across the six spectral bands,

water and bare ground were identified in the classified image in the first iteration. Brightness values for water were higher in the blue band and continued to gradually decrease in subsequent bands. On the other hand, the brightness values for bare ground were the lowest in the blue band and continued to increase in successive bands. Pixels in the original Landsat image corresponding to water and bare ground were masked out and the remaining pixels were reclassified and assigned to 75 clusters. Reference data were used to identify reeds (class 1), reeds and other vegetation (class 2), and other vegetation (class 3) from the classified image. Reeds had relatively high reflectance values in the near infrared region (band 4) in comparison to other vegetation. Minor changes were noticed in the reflectance values in the reeds due to differences in the growth stages. Reflectance values were slightly lower for the reed beds along water bodies in comparison to those reed beds that were further away.

The overall classification accuracy of the Landsat image was 84% (Table 2), and the individual class accuracy values were 90% or more for reeds, bare ground, and water bodies (classes 1, 4, and 5). Individual class accuracy was the lowest for the other vegetation (class 3) at 53%. Omission error for reeds (class 1) was 10% due to the misclassification of three verification sites as reeds and other vegetation (class 2). However, most of the verification points (28 out of 31, or 90%) for reeds (class 1) were correctly identified in the Landsat image. Of the 14 reed and other vegetation (class 2) verification sites, three were misclassified as reeds (class 1) and the remaining 80% of the sites was correctly identified in the image. The class accuracy was the lowest for other vegetation (class 3), as most of the verification points belonging to this class were misclassified as either reeds (class 1) or reeds and other vegetation (class 2). Of the 34 verification points belonging to the other vegetation class, eight (24%) were misclassified as reeds and five (15%) were misclassified as reeds and other vegetation. The omission error was 5% for bare ground (class 4), as

Verification data	Map classes					Total	OE (%)
	1	2	3	4	5		
1 – Reeds	28	3	0	0	0	31	10
2 – Reeds and other vegetation	3	11	0	0	0	14	21
3 – Other vegetation and reeds	8	5	18	3	0	34	47
4 – Sandy soil and sparse vegetation	0	2	1	55	0	58	5
5 – Water	0	0	0	0	18	18	0
Total	39	21	19	58	18	155	
CE (%)	28	48	5	5	0		
Overall accuracy: 84%	κ agreement index: 0.7869						

OE, omission error; CE, commission error.

Table 2 Error matrix for the classified Landsat image based on 155 verification points, and associated error metrics for the vegetation and land cover classes mapped

most of the verification points (55 out of 58; 95%) were correctly identified in the image. All the verification sites belonging to water (class 5) were correctly identified.

Commission error for reeds (class 1) was 28%, as verification sites belonging to reeds and other vegetation (class 2) and other vegetation (class 3) were misclassified as reeds (Table 2). Out of the 39 sites identified in the image as reeds, only 28 were reeds and the remaining 11 sites belonged to classes 2 and 3. Ten verification sites belonging to classes 1, 3, and 4 were misclassified as reeds and other vegetation (class 2), hence the commission error was highest (48%) for this class (Table 2). Because the number of instances of misclassification was lower for classes 3, 4, and 5, their commission error values were 5, 5, and 0%, respectively. The κ agreement index, which takes into account both omission and commission errors in the classified images, was 0.79 (Table 2). The maximum value for this agreement is +1, which would indicate complete positive agreement between the classes identified on the image and the corresponding classes on the ground.

Reeds (class 1) occupied 21% (437 098 ha) of the total area mapped in this study (Figure 1). Reeds and other vegetation (class 2) and other vegetation (class 3) were slightly more than 1% each (28 466 and 29 007 ha, respectively). Shrubs, grasses, and forbs (other vegetation) generally dry out at the end of the summer, which could have resulted in lower estimates of class 3. A major portion (73%, that is, 1 525 395 ha) of the study area was bare ground, whereas water bodies were found in 3% (54 797 ha) of the study area. Areas with dry, sparse vegetation were classified as bare ground due to low reflectance.

Locust nymph presence and vegetation type

In 37 locations, nymphs were present in bands with densities ranging between 100 and 2 000 per m². They were predominantly in the second and third instar and exhibited a straight pronotum and contrasting red and black coloration, which characterizes the gregarious phase phenotype (Bei-Bienko & Mistschenko, 1951).

At 28 out of the 37 sites (76%) that had nymphs in 2007, reeds were the dominant vegetation in 2006. Among them, at 15 sites, reeds were the only vegetation type present within the 20.25 ha window (Table 3). At seven sites, reeds constituted more than 75% of the vegetation type and the remaining six sites had reeds between 51 and 67%. Bare ground was the majority land type at the nine remaining sites. Two of these locations had only bare ground, and the other seven sites had some vegetation, mostly reeds (class 1). In other words, we found only two sites with bare ground in August 2006 that had nymphs in June 2007.

Table 3 Relationship between the presence of Asian migratory locust, *Locusta migratoria migratoria*, nymphs in June 2007 at 37 sites and the proportion of reeds at each site in August 2006

Reeds (%)	Sandy soil (%)	Number of sites with nymphs
100		15
80–99		7
60–79		4
40–59		2
	100	2
	80–99	0
	60–79	3
	40–59	3
	20–39	1

Discussion

Spectral reflectance values for reeds were distinct from any other vegetation class. Subtle differences in reflectance values were noticed between the reeds growing along the edges of the water bodies and those that were growing away from the water bodies. When reeds were present along the edges of the water bodies, their infrared (band 4) reflectance values decreased slightly. Similar decreases were noticed in other reed locations, which could be due to leaf senescence. At the end of the growing season, the chlorophyll content in the leaves decreases, resulting in a reduction in the amount of infrared reflection (Jensen, 2000). However, these differences did not pose any difficulties in identifying the reeds. The spatial resolution of Landsat (30 m) was adequate to capture not only large, continuous reed stands, but also narrow bands of reeds growing along canals and agricultural fields (Figure 2). Presence of clouds and shadows in a Landsat image could decrease its usefulness. Under these circumstances, other medium resolution data (currently collected, for example, by SPOT and IRS satellites) could be used as alternatives, as not all satellites collect information on the same day for a given location.

The κ agreement value of 0.79 obtained for the overall map (Table 2) is close to an excellent (κ value > 0.8) agreement (Congalton & Green, 1991). When reeds were present in a mixture with other vegetation, the infrared (bands 4 and 5) and green (band 2) reflectance values decreased in comparison to sites that had pure reeds (class 1). However, misclassification of other vegetation types as reeds was a problem that could result in the overestimation of areas under reeds (Table 3). Approximately 24% of the other vegetation sites were misclassified as reeds, and this could be due to the fact that the vegetation type at those locations could have had different reflectance values. One approach to minimize such error would be to have a more detailed classification scheme for other vegetation classes instead of

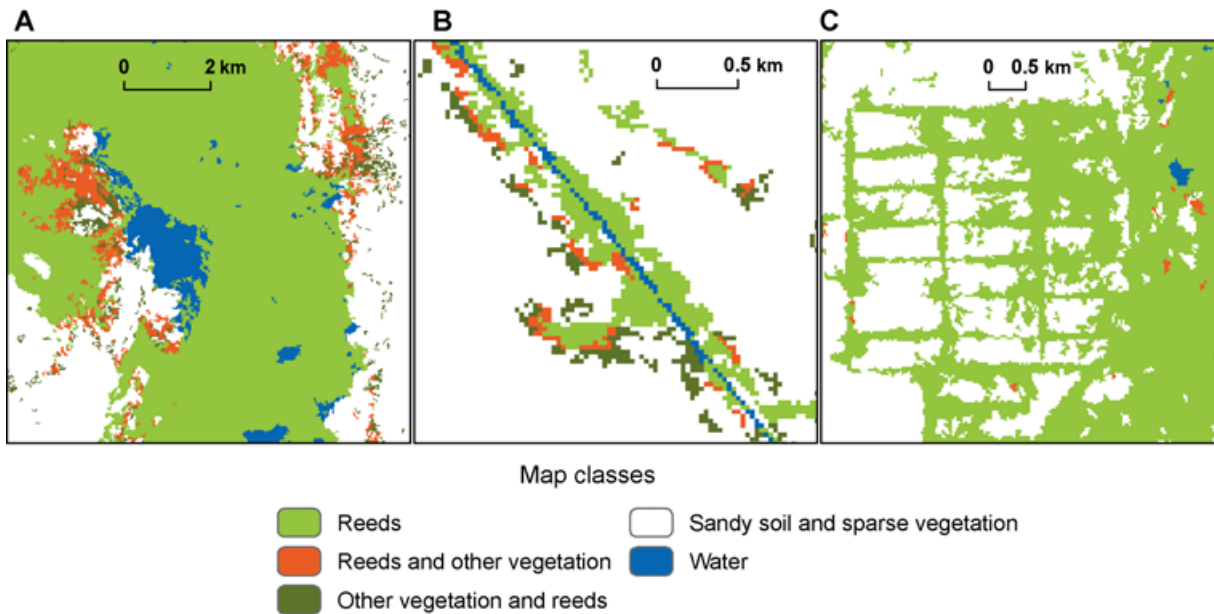


Figure 2 Classified Landsat image showing reeds growing (A) in patches, (B) along a canal, and (C) along edges of agricultural fields in the Amudarya River delta, Uzbekistan.

the current approach of grouping several vegetation types under a single class. However, for rapid and periodic assessment, and from a locust management standpoint, an overestimation of reed area might be more acceptable than an underestimation.

Asian migratory locust nymphal bands were found to be associated predominantly (76%) with reeds (class 1) and, to a lesser extent (10%), with reeds and other vegetation (class 2). Altogether, these two classes occupied 22% of the study area (Figure 1). This means that if a locust surveyor was looking for nymphs, the chances of finding them were about five times higher within the reeds than elsewhere. How can these results be relevant to the egg-pod locations in the previous year? In order to answer this question, it is necessary to consider the migration capacity of the nymphs. Although *L. migratoria migratoria* is well-known for its migratory habits, as follows from its name, the early instars are much more sedentary than the late ones (Uvarov, 1977). The nymphs we found belonged to the gregarious phase, for which daily marching behavior is typical (Novitsky, 1963). However, the marching speed and the extent of the displacement depend on many factors, with the nymphal age, vegetation density, and weather being the most important (Uvarov, 1977). According to Tsyplenkov (1970), the total distance traveled by AML during its nymphal stage can reach 30 km. However, the first- and the second-instar nymphs rarely move more than a few meters from their hatching sites. The third-instar nymphs may cover distances up to 300 m a day, but only if

they march on bare ground. If the vegetation density is high (>20 reed stems per m^2), even the third-instar nymphs do not move more than 10 m a day (Tsyplenkov, 1970). In the area studied, reed density in the locations where the AML nymphal bands were found was usually much higher than 20 stems per m^2 . Furthermore, in the beginning of June 2007, daily air temperatures in the Amudarya delta were relatively cool and it rained several times. These factors also dramatically reduce the locust nymphal migratory capacity (Uvarov, 1977), which means that by the time of our ground surveys on 15–17 June, the locust nymphs did not move more than a few dozen meters from their hatching sites. This fits within the spatial ‘window’ of 20.25 ha that we built around every nymphal location in our analysis. These assumptions allowed us to consider that the locations in which we found nymphal bands in June 2007 were approximately the same where the females laid their eggs in the previous year.

The fact that $>75\%$ of young *L. migratoria migratoria* nymphs and, consequently, egg-pods were found within the reeds suggests that this vegetation class should occupy the central place in the ground egg-pod surveys by locust control specialists. Information on the reed spatial distribution derived from satellite data should provide the locust workers with the ‘first cut’ through the wetland habitats and minimize unnecessary examinations of other land cover types. Certainly, not every reed area would harbor locust egg-beds, and finding them still remains a tedious task on $>400\,000$ ha of reeds identified in the image. However, the satellite-derived

data would be very useful at guiding locust field workers to potential locust oviposition sites, and save them a tremendous amount of time and resources compared to traditional, indiscriminate (and thus practically 'blind') surveys. The image classification technique used in this study is a robust methodology that does not require large amount of calibration data, and could be completed within a day or two after an image is acquired. Reed distribution maps could be generated every year to coincide with the AML egg-laying (August) and hatching (May) using Landsat or other medium resolution satellite data that are collected periodically.

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