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Land cover in Upper Egypt assessed using regional and global land cover products derived from MODIS imagery

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Abstract

Irrigation along the Nile River has resulted in dramatic changes in the biophysical environment of Upper Egypt. In this study we used a combination of MODIS 250 m NDVI data and Landsat imagery to identify areas that changed from 2001–2008 as a result of irrigation and water-level fluctuations in the Nile River and nearby water bodies. We used two different methods of time series analysis -- principal components (PCA) and harmonic decomposition (HD), applied to the MODIS 250 m NDVI images to derive simple three-class land cover maps and then assessed their accuracy using a set of reference polygons derived from 30 m Landsat 5 and 7 imagery. We analyzed our MODIS 250 m maps against a new MODIS global land cover product (MOD12Q1 collection 5) to assess whether regionally specific mapping approaches are superior to a standard global product. Results showed that the accuracy of the PCA-based product was greater than the accuracy of either the HD or MOD12Q1 products for the years 2001, 2003, and 2008. However, the accuracy of the PCA product was only slightly better than the MOD12Q1 for 2001 and 2003. Overall, the results suggest that our PCA-based approach produces a high level of user and producer accuracies, although the MOD12Q1 product also showed consistently high accuracy. Overlay of 2001–2008 PCA-based maps showed a net increase of 12 129 ha of irrigated vegetation, with the largest increase found from 2006–2008 around the Districts of Edfu and Kom Ombo. This result was unexpected in light of ambitious government plans to develop 336 000 ha of irrigated agriculture around the Toshka Lakes.

Keywords

MODIS NDVI; Upper Egypt; irrigated vegetation; time series analysis; Toshka Lakes; MOD12Q1

1. Introduction

In the hyper-arid desert of Upper Egypt, annual rainfall is typically negligible (Bastawesy *et al.* 2008) and irrigation from the Nile River is generally the only water source to sustain permanent agriculture and other forms of primary production. Besides increasing crop coverage and regional photosynthetic activity, irrigation can produce changes in local and regional climatic conditions (Sen Roy *et al.* 2010), may lead to soil salinization (Thomas and Middleton 1994), and create new habitats for vectors associated with diseases such as

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schistosomiasis, malaria, Rift Valley Fever (RVF) and West Nile Virus (WNV) (Harrus and Baneth 2005). The Egyptian government has implemented various large-scale water management and diversion schemes to stabilise water delivery for irrigation, including the completion of the Aswan High Dam in 1968, which created Lake Nasser, and the Toshka spillway that flooded the Toshka Depression and created four new lakes in 2001 (Bastawesy *et al.* 2008). These major water bodies created incentives and opportunities for new irrigation schemes, most notably the creation of new canals that were intended to produce 336 000 ha of new irrigated area around the Toshka Lakes to increase crop production and move people to the region (Lonergan and Wolf 2001).

Our study area (figure 1) contains few land cover types relative to more humid regions and photosynthetic activity that is limited by irrigation and lake water levels; thus the area provides a simple case to evaluate land cover maps using different sources of multitemporal, multi-resolution vegetation index imagery. Upper Egypt receives almost no rainfall with monthly evaporation rates ranging from 115–300 mm from winter to summer when daily maximum temperatures typically exceed 45°C (Bastawesy *et al.* 2008). The vegetation of the study area is concentrated along the Nile north of Aswan and consists of intensive sugar and some cotton cultivation, particularly around the Districts of Edfu and Kom Ombo (figure 1). In less intensively managed areas along the margins of Lake Nasser, Ali *et al.* (2000) reported the presence of riparian phreatophytic vegetation characterized by *Tamarix nilotica* and therophytes such as *Glinus lotoides* mixed with wetland species such as *Typha domingensis*. This semi-natural vegetation tends to be found on moist alluvial soils and is intensively grazed (Ali *et al.* 2000). With changes in lake levels over the past decade, particularly in the Toshka Depression, wetlands have contracted or disappeared in some areas (Bastawesy *et al.* 2008).

Recently, there has been growing interest in using remote sensing to monitor the changes in open water and irrigated areas associated with new and existing irrigation activities in Upper Egypt. For example, Chipman and Lillesand (2007) used imagery from the Moderate Resolution Imaging Spectroradiometer (MODIS) and data from a laser altimeter to document changes in the lake levels in the Toshka Depression. Bastawesy *et al.* (2008) used imagery from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and Système Pour l'Observation de la Terre (SPOT) imagery to document water loss in these same water bodies. Elewa *et al.* (2010) used Landsat Enhanced Thematic Mapper Plus (ETM+) imagery to identify geologic faults near the Toshka Lakes where aquifer exploitation may be feasible. Here, we utilize a combination of MODIS and Landsat imagery to map water-driven changes in the vegetation covering most of southern Egypt, northern Sudan, and including Lake Nasser, The Toshka Depression, Aswan and major irrigation areas around the Districts of Edfu and Kom Ombo to the north of Aswan City (figure 1).

Consistent with other studies that have shown high temporal resolution imagery (< 10 day repeat interval) for monitoring managed vegetation (Alexandridis *et al.* 2008), we utilized 8-day MODIS 250 m Normalized Difference Vegetation Index (NDVI) imagery to identify irrigated and riparian vegetation, barren desert and water bodies on an annual basis. Such image composites should be well-suited for desert environments such as Upper Egypt, which has low cloud cover throughout the year and frequent, short-term changes in irrigation status through the control of irrigation canals and pumping stations. The major aims of the study, therefore, were to develop an operational mapping approach using regional, coarse-resolution optical imagery from 250 m MODIS NDVI imagery to detect changes in vegetation from 2001–2008, and to compare these results with a new MODIS global land cover product, MOD12Q1 version 5 (Friedl *et al.* 2010). In this way, our study contributes to a growing array of studies that evaluate the utility and accuracy of different

MODIS products (e.g., Heiskanen 2008, Vancutsem *et al.* 2010, Wang *et al.* 2010). We are unaware of any previous studies that have systematically evaluated the MOD12Q1 global land cover product in an arid environment and compared it with approaches that use regionally specific training and testing data.

2. Data and Methods

We obtained 2001–2008 version 5 MOD09Q1 250 m 8-day reflectance imagery for MODIS bands 1 (620–670 nm) and 2 (841–876 nm) covering Upper Egypt from <https://wist.echo.nasa.gov/api/>. These data were used to create a temporal sequence of 8-day NDVI images, which were re-projected to a UTM coordinate system, to produce a higher temporal resolution product than the standard 16-day MODIS 250 m NDVI product (MOD13Q1). Thus, each year in our time series contained 46 NDVI composite images sufficient to evaluate change in vegetation cover based on annual phenological patterns. We applied two different time series methods to the 8-day NDVI composites: standardised principal components analysis (PCA) and harmonic decomposition (HD). Both methods have been used to analyze NDVI time series, reduce data volumes to simplify analysis of phenological patterns and remove image noise by eliminating high frequency components associated with cloud cover, atmospheric effects or sensor calibration issues (Eklundh and Singh 1993, Roerink *et al.* 2000). Standardised PCA produces a set of images that define a rotation of the original images in such a way that new axes are orthogonal and point in the direction of decreasing order of the variances (Eklundh and Singh 1993). HD produces a set of amplitude and phase images that correspond to the underlying frequencies present in the raw time series and is analogous to temporal Fourier analysis although it uses exact calendar dates of the images and can use irregularly spaced observations unlike Fourier analysis. Both methods were implemented in Earth Trends Modeler, which is available in the Idrisi Taiga version (Eastman 2009). Readers unfamiliar with these techniques are referred to Eklundh and Singh (1993) and Roerink *et al.* (2000) for further information.

A set of eight Landsat 5 TM and Landsat 7 ETM+ images (table 1) obtained from the US Geological Survey (<http://glovis.usgs.gov/>) was used to develop training areas and perform classification accuracy assessments. The Landsat imagery allowed identification of three clearly distinguishable land cover types: irrigated vegetation (IV), desert areas and open water. Two images were used to develop training polygons that were entered into a back-propagation neural network (BPNN) classifier and five additional images were used to develop a set of validation polygons that were used in subsequent classification accuracy assessment. Although we did not use randomly sampled validation polygons, the number of validation pixels (table 1) appeared sufficient to provide a representative sample (Foody 2009).

Both the PCA and HD image outputs were treated analogously to single image bands in standard multispectral image classification and were entered into the BPNN. For the PCA images, we varied the inputs experimentally to include the first four, six and eight principal components and for the HD images we input the first four amplitude and four phase images. The BPNN parameters including image inputs, iterations, hidden layers, and layer nodes were adjusted experimentally until qualitatively acceptable classifications were produced for subsequent quantitative analysis using the error matrix. Two summary classification statistics were calculated, Cramer's V, which ranges from zero for no agreement to 1 for perfect agreement, and percentage correctly classified (PCC).

To evaluate these products against a standard, global product, we included the MODIS yearly land cover product (MOD12Q1, collection 5) in our analysis. This 500 m product is based on a regression tree method applied to MODIS bands 1–7 and other inputs such as

land surface temperature, albedo and texture and is produced from 32-day average values from original 8-day products, which reduces missing data from cloud cover (Friedl et al. 2010). From MOD12Q1, we selected the International Geosphere-Biosphere Programme (IGBP) classification scheme, which appeared most appropriate for our study region, and we aggregated the classes to produce a new three-class map consistent with our classification. The accuracy of the simplified MOD12Q1 IGBP was then evaluated alongside the regionally specific PCA- and HD-based products.

3. Results

Experiments varying the inputs to the BPNN revealed that the most realistic land cover classifications were produced using the first four principal components for the PCA-based inputs and a combination of the first four amplitudes and two phase images from the HD-based inputs. Additional PCA or HD products tended to result in highly erroneous maps that had low levels of training accuracy. We found that a three-layer BPNN including one hidden layer parameterized with 10,000 iterations, a learning rate of 0.01, a momentum factor of 0.5 and sigmoid constant of 1.0 produced the best classification results. The PCC and Cramer's V values showed that the accuracy of the three different land cover products was comparable for 2001 and 2003; whereas PCC and Cramer's V (97.8 and 0.976, respectively) revealed that the PCA-based classification produced the highest accuracy for 2008 (table 2). The PCA-based classification worked particularly well for areas of intensive irrigated vegetation. This high level of accuracy suggests that the version 5 MODIS 250 m reflectance product provides a highly consistent source of information about the desert land surface that is largely free of atmospheric and directional reflectance effects. Nonetheless, for the three classification methods some errors were apparent. In all cases, the largest errors involved the vegetation class, in which small patches of vegetation were classified as desert. For example, this error ranged from 0.072 for the 2008 PCA classification to 0.210 for the 2008 MOD12Q1 product. Visual inspection of the classified images revealed that many of these omissions related to small areas of semi-natural riparian vegetation or small, isolated irrigated areas, which suggests that small features visible in the Landsat TM and ETM+ scenes were sometimes missed in the 250 m MODIS product and the coarser 500 m MOD12Q1 product (figures 2 & 3). However, commission errors were generally quite small, ranging from 0.000 for the open water class in the PCA-based 2001 classification to 0.120 in the HD-based 2008 classification.

Generally, sources of disagreement between the MOD12Q1 and PCA-based products appeared along the margins of major water bodies in which inundated areas such as small islands or the shoreline were sometimes classified as vegetation. Figure 2 shows both the MODIS PCA based classification and the MOD12Q1 for 2008 and reveals areas of agreement and disagreement for the whole study area. The HD based product is not shown as it produced lower classification accuracies than either the PCA or MOD12Q1 products (table 2). The finer scale MODIS PCA product correctly identified water-desert boundaries, while the MOD12Q1 appeared to confuse these areas around Lake Nasser (see figures 2 & 3) as riparian or irrigated vegetation. In addition, the PCA-based product correctly identified a substantial area of newly irrigated land to the east of Kom Ombo district, which represents the largest area of expanded irrigation over the period of our study. Notwithstanding minor sources of error related to omissions, the accuracy of the PCA-based product suggests that this approach is sufficient for operational monitoring of water-driven changes in vegetation cover. Overlay of the 2001 and 2008 maps derived from the PCA-based method reveal a modest increase in irrigated vegetation from 2001–2008 (12 129 ha), with most of this observed as extensions of existing irrigated areas around Edfu and Kom Ombo (figure 3).

4. Discussion and Conclusions

Time series of 250 m MODIS NDVI imagery provide a rich data source for creating annual land cover and change maps in a variety of different biomes. The 8-day temporal resolution used in our study appeared particularly appropriate for identifying areas of vegetation and water level change in this desert environment and the spatial resolution is considered a good compromise between spatial and temporal resolution for global land change monitoring (Justice and Townshend 1988). The 250 m resolution also presents certain advantages to identify sites for potential field investigation as field sampling within 250 m cells is generally less labor intensive than in larger cells provided by 500 m or 1 km land cover products. Future work using a segmentation algorithm may also be used to create a finer classification scheme based on a combination of Landsat and MODIS 250 m NDVI images. Overall, we found that the PCA-based product clearly meets our main objective to accurately map water-driven changes in vegetation cover at 250 m spatial resolution.

Our results show that ambitious plans to irrigate 336 000 ha of desert land for agricultural production in the Toshka Depression have yet to be realized and the decrease in the surface area of the Toshka Lakes is consistent with previous remote sensing studies conducted by Chipman and Lillesand (2007) and Bastawesy *et al.* (2008). If plans to complete irrigation do come to fruition, a large influx of people and water near the border with Sudan is likely to present a series of major public health and environmental issues.

The PCA-based method developed here outperformed the MODIS 12Q1 and HD-products, although all three produced acceptable results in terms of classification accuracy (Yuan and Elvidge 1998). A similar study conducted in a semi-arid region of northeast Australia also found that the MOD12Q1 produced reasonable agreement with a regionally specific land cover classification for a semi-arid part of northeast Australia (Schottker *et al.* 2010). Although the MOD12Q1 provided an accurate land cover product for Upper Egypt, we conclude that ecological studies requiring highly accurate environmental data should use 250 m NDVI time series data to derive regionally specific land cover maps and change classes. Future efforts to improve the MOD12Q1 product may include more regionally specific training and testing data, downscaling of the first seven 500 m bands to 250 m to improve spatial resolution (e.g., Luo *et al.* 2008), and further exploitation of growing information contained in the decadal archive of NDVI data emanating from the MODIS Terra sensor (Friedl *et al.* 2010).

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Figure 1. Map of the study area: (a) Detailed view of the study area showing the location of major water bodies and districts associated with irrigated vegetation overlaid on a MODIS NDVI image from August 2008; (b) Inset showing the study area in Africa north of the equator.

Figure 2. 2008 MODIS land cover maps for Upper Egypt derived from different sources for the study area: (a) 250 m PCA-based classification; (b) 500 m MOD12Q1 classification; (i) and (ii) indicate areas around Kom Ombo and Edfu Districts and around one of the lakes in the Toshka Depression, respectively, displayed in figure 3 below.

Figure 3. Detailed views of the 250 m PCA-based classification, 500 m MOD12Q1 classification and corresponding Landsat false color images: Kom Ombo and Edfu Districts shown in (a) 250 m PCA-based classification, (b) 500 m MOD12Q1, and (c) Landsat 5 false color image; a portion of the Toshka Depression shown in (d) 250 m PCA-based classification, (e) 500 m MOD12Q1, and (f) Landsat 7 ETM+ SLC-off image.

Table 1

Landsat 5 TM and 7 ETM+ images used for training set development and validation of images classified using PCA and HD time series methods. For Landsat 7 images, scan line corrector (SLC) status is indicated.

Image Path/Row	Satellite/SLC Status	Date	Use(s)
174/43	Landsat 7/On	16-Nov-2001	Training
174/43	Landsat 5	27-Sep-2003	Training and validation
174/43	Landsat 5	30-Jan-2009	Training
174/43	Landsat 7/Off	12-Jun-2008	Validation
174/42	Landsat 5	30-Jan-2009	Validation
174/44	Landsat 5	30-Jan-2009	Validation
175/44	Landsat 7/Off	02-Mar-2009	Validation
175/44	Landsat 7/On	13-Apr-2001	Validation

Table 2

Classification accuracies of different map products derived from MODIS imagery based on validation polygons derived from Landsat 5 and 7 imagery: Two regional products, based on principal components analysis (PCA), and harmonic decomposition (HD) and a global product, MOD12Q1 collection 5.

Year	Classification	Percentage Correctly Classified (PCC)	Cramer's V	Number of validation pixels
2001	PCA	97.8	0.948	4796
	HD	97.2	0.925	
	MOD12Q1	97.6	0.944	
2003	PCA	99.7	0.970	16347
	HD	98.3	0.854	
	MOD12Q1	99.3	0.951	
2008	PCA	97.8	0.967	6780
	HD	90.1	0.840	
	MOD12Q1	92.4	0.879	