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Monitoring environmental change and degradation in the irrigated oases of the Northern Sahara

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A B S T R A C T

Salinization caused by irrigation mismanagement is a major cause of desertification. Monitoring of land degradation caused by salinization and other processes has been subject to international scientific debates leading to the commitment by global decision-makers to address these threats collectively through the UNCCD. This paper discusses the experience of monitoring land and water degradation in the salinity-prone irrigated arid environments of the Northern Sahara in light of current international scientific developments affecting both conceptual and methodological approaches.

The paper integrates a range of simple and accessible methods to achieve a multidisciplinary analysis including remote sensing, use of national research archives, interviews with decision-makers and direct surveys of cultivators. Revised assessments of the extent and ecological processes of salinization emerge from the analysis. As irrigated areas expand globally, the new conceptual and methodological techniques in dryland development science have the potential to enable scientists in affected areas to contribute to global efforts to monitor degradation effects caused by desiccation, salinity and human responses.

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1. Introduction

The extent of irrigated agriculture in arid environments is growing globally (Kijne, 2003; WWAP, 2009). The main drivers are increasing demand for agricultural production, growing climatic threats to rainfed production, and the spread of groundwater extraction technologies. Salinization caused by irrigation mismanagement is well-recognized as a major cause of land degradation in drylands (known globally as 'desertification') (Thomas and Middleton, 1993; UNCCD, 1994; Worthington, 1977). Salinization is a process whereby the proportion of salt content in soil or water is increased. This is detrimental to agricultural productivity because it disrupts plant water-use patterns, and leads to increased requirements for water and labor to leach or replace salt-affected soils (Kijne, 2003; Ghassemi et al., 1995). Irrigated systems are not usually adaptable to increasing water scarcity, which can trigger deepening cycles of overexploitation and degradation (Puigdefábregas and Mendizabal, 1998). A generic desertification pathway through salinization has been conceptualized as follows: '*Traditional oases > large scale irrigation > booming non agrarian uses > water degradation > vegetation degradation > sandification*' (Geist, 2005).

During the 1980s, the loss of agricultural land through water logging, salinization and alkalinization was estimated at 1.5 million ha annually (e.g. in Brundtland, 1987). Had this been correct, and had the trend continued, 240,000 square kilometers would have been lost over the past 16 years, which is an area approaching the size of the British Isles (244,820 square kilometers). More recent global and regional assessments of land cover change (e.g. Bai et al., 2008; Helldén and Tottrup, 2008) have not been able to quantify effects associated with the expansion of salinization in irrigated areas. In response to international pressure to improve the monitoring of global trends in land degradation and desertification, the international scientific community has searched for new conceptual and methodological approaches to better inform decision-makers (Reynolds et al., 2007; Stafford Smith and Reynolds, 2002; Vogt et al., 2011).

Although salinization is recognized as one of the major causes of land degradation and desertification in drylands (Nachtergaele et al., 2011), the use of the Aridity Index (relating precipitation to evapotranspiration) to limit the definition of areas addressed by the UNCCD has discouraged consideration of the growing areas of

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arid and hyper environments that have come under irrigated agriculture (Thenkabail et al., 2009; WWAP, 2009). In these environments, rainfall is not the only source of water used in evapotranspiration and human populations enjoy a range of available technical options enabling modification of local microclimates and productive land uses. Irrigation is also increasingly being introduced to control agricultural water application in less arid areas where climates may be variable. In each case, the mix of climatic, biophysical and socio-economic factors involved differs, depending on context.

This paper takes a fresh look at the salinization-desertification challenge in light of both conceptual and methodological developments that have been introduced for monitoring and assessment of salinization as a land degradation process over the past twenty years. The question is approached through two case studies in the Northern Sahara, where salinity, water scarcity and management innovation may be considered to be acute and relatively advanced and salinization has been recognized as a perennial cause of land degradation (Kassas, 1995). The paper investigates the following questions:

- what insights have been enabled through the increased availability of materials and methods for land cover change detection?
- how do these insights connect to other ongoing national and scientific efforts to monitor, model and assess land salinization and degradation trends in the two selected cases?
- what conclusions can be drawn from these cases for international scientific efforts to contribute to the monitoring of land degradation in arid regions under threat from salinization?

2. The new conceptual approach to assessing development and change in drylands: application to salinization in arid environments

Over recent decades, research and practice in dryland development science have generated a set of general lessons concerning the condition and dynamics of human environment systems (Reynolds et al., 2007; UNCCD, 2009). These have gained recognition as guiding principles enabling more effective interpretation of environmental development, changes and degradation, including salinization:

(a) *Both researchers and practitioners need to adopt an integrated approach; ecological and social issues are fundamentally interwoven, as are the options for livelihood support and ecological management;*
(b) *There needs to be heightened awareness of slowly evolving conditions; short-term measures tend to be superficial and neither resolve persistent problems nor deal with continual change;*
(c) *Nonlinear processes need to be recognized. Dryland systems are often not in equilibrium, have multiple thresholds, and thus often exhibit multiple ecological and social states;*
(d) *Cross-scale interactions must be anticipated; problems and solutions at one scale influence, and are influenced by, those at other scales;*
(e) *A much greater value must be placed on local environmental knowledge.*

This conceptual approach is helpful in highlighting the need to consider both temporal and spatial patterns of changing salinity. Points b) and c) reflect the prevalent view that scientific understanding of environmental change in drylands has lagged behind science in more temperate areas because it took time to understand disequilibrium theories regarding long term change (Thomas and Middleton, 1994). In light of this, recent scientific contributions have emphasized the importance of monitoring 'internal controlling drivers', such as water availability, which are termed 'fast' changing, and connecting them up to "slow" external drivers resulting from processes on a wider scale, such as landscape function, land use and climate change relating to persistent changes in ecosystem function (Gunderson and Holling, 2002; Stafford Smith and Reynolds, 2002). Salinization has been conceptualized as a slow change, resulting from fast increases in productivity achieved through irrigation (Verstraete et al., 2009).

The sensitivity of different irrigated crops to increases in salinity varies (FAO, 2002). For *Phoenix dactylifera*, L. (date palm), a threshold of Electrical Conductivity (EC) 4 dSm (4000 $\mu S/cm^{-1}$) for salinity effects on fruit yield has been published. However, reflecting point c), above, the effects of salinity on plant productivity are not linear, and can interact with other stress factors (FAO, 2002; Flowers and Colmer, 2008). Furthermore, consideration of both the degree and rapidity of the salinization process is important in determining farmers' options to adjust their management practices.

Geist (2005) classifies increases of salt content in water from a given baseline as follows: (<25% = slight, 25–50% = moderate, 50–75% strong and 75–100% extreme). The same classifications are applied for increases in a salinized area or vegetation change. These changes are observable through simple conventional methods for field sampling of EC or Total Dissolved Solids (TDS),[1] or through remote observation of trends in vegetation cover. Extreme changes according to this classification can conceivably take place in the space of a year. Therefore, while salinization may be conceptualized as "slow", the timeframe within which changes may be observed is not necessarily an obstacle to scientific measurement. Although time series of data over decades are desirable to determine processes and trends in salinization, a few years of consistent monitoring can sometimes be enough. This is fortunate, since once an area of land or a well is too saline to use, monitoring tends to cease.

In light of points a and e), above, it has been argued for some time that land degradation should be understood differently by scientists (Reynolds et al., 2007; Stafford Smith and Reynolds, 2002; Vogt et al., 2011). Few physical processes are irreversible. This is true of salinization. Some of the most effective techniques for soil conservation and salt removal have been practiced for centuries (Rhoades et al., 1992). More recent innovations, such as hydroponics, are changing the fundamental requirements for soil and water for cultivation. Salts can be flushed away from soils, or desalinated out of water. Waterlogged areas can be pumped. Even salinized aquifers can be remediated through artificial recharge. This renders the available definitions of degradation in terms of biophysical irreversibility ever more socio-economic, bringing with them questions as to who might or might not pay the costs to reverse degradation.

3. Description of study areas and context

Two study areas in the Northern Sahara have been included in this investigation: the Nefzaoua region in Southern Tunisia, and the North of the Western Desert of Egypt (Fig. 1). Each extends from a relatively developed and accessible area to a more remote and less developed area. In the Nefzaoua region, the North-South extent of the study area is 72 km. The South is more arid, receiving an annual average close to 50 mm of rainfall per year, compared to around

[1] There is a non-linear relationship between these measures – see Hem 1985.

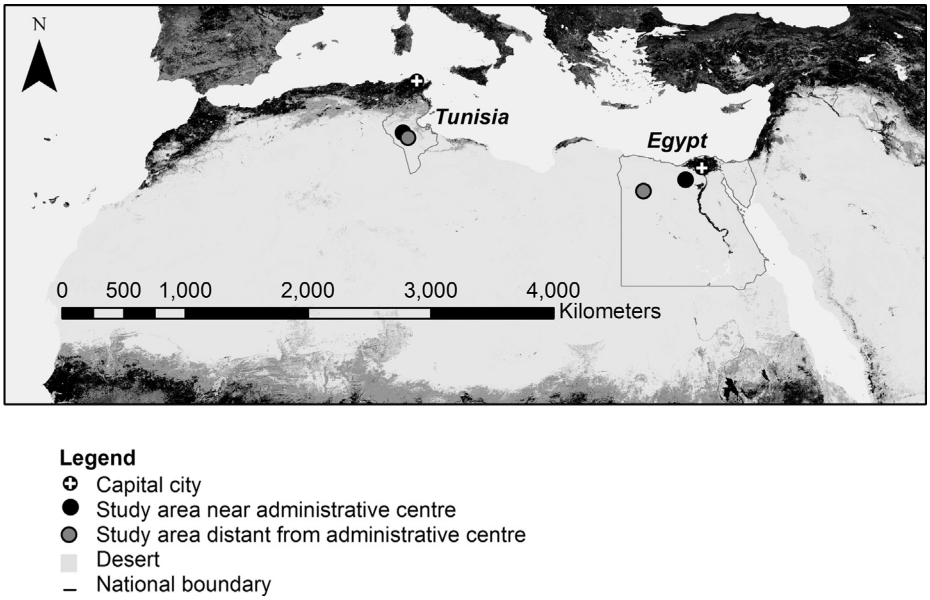

Fig. 1. Location of study areas.

100 mm in the North. Since the area of the study region is approximately 3,456 km^2, the average annual volume of rainfall is around 26 million cubic meters. However, a conservative estimate of the volume of groundwater used for irrigation each year since the 1990s would be somewhere around 350 million cubic meters, based on available national statistics. The Western Desert of Egypt is even more arid and dependent on irrigation. At its North-Eastern edge, Wadi El Natrun, is relatively close to the Nile Delta, and receives below 50 mm of rainfall on average per year. Siwa, 600 km to the South-West, is more remote and receives below 10 mm on average per year. Farmers using traditional flood irrigation systems apply around 10 mm of water *each time* they irrigate. In the summer, this may be several times per week. In both regions, daily mean temperatures vary between 10 °C in the winter to 32 °C in the summer, with the hottest temperatures in August.

Climate change taking place in North Africa over multi-millennial timescales has led to the region experiencing multiple episodes of conditions wetter than today, interspersed with dry phases. The surface water resources available in this region today are limited under arid conditions, but a legacy of groundwater resources remaining from wetter conditions during the late Quaternary, are a significant asset. The major regional aquifer systems are at depths of around 1000 m (Edmunds et al., 2003; Sundborg and Nilsson, 1985) (Fig. 2). In the North West Sandstone Aquifer System (NWSAS) beneath the Nefzaoua region, the deep Continental Intercalaire (CI) aquifer is overlain by the Complexe Terminal (CT). In the Western Desert, the Nubian Sandstone Aquifer System (NSAS) in the Upper Cretaceous is overlain by the Miocene Aquifer in the Post-Nubian Aquifer System (PNAS). The groundwater systems feed springs that emerge through geomorphological depressions in the desert landscapes, creating endorheic, or closed, basins around saline lakes and *sebkhas*. Local micro-climates are altered through the presence of the waterbodies and irrigation. These environments support *P. dactylifera* L. other halophytic vegetation, and salt-tolerant crops. Irrigation is used to increase their extent and productivity.

Scientific investigations of the causes and processes of salinization have identified water-logging in the low-lying areas close to the *Chott El Djerid* in the Nefzaoua region, and at Siwa in the Western Desert (Masoud and Koike, 2006; Misak et al., 1997). In these diagnoses, the inefficiency of water use by farmers has often been blamed for causing secondary salinization (Askri et al., 2010; Gad and Abdel-Baki, 2002; Marlet et al., 2009). Such diagnoses justify the installation of extensive drainage structures, energy-intensive pumping systems, and controversial proposals for water-transfer projects, threatening the surrounding desert habitats (Abo-Ragab, 2006). Where the salinity of groundwater has increased over time, inappropriate well-design has sometimes been blamed, leading to suggestions for the improved engineering of wells. On the other hand, regional salinization processes taking place across the aquifer systems due to falling water tables,

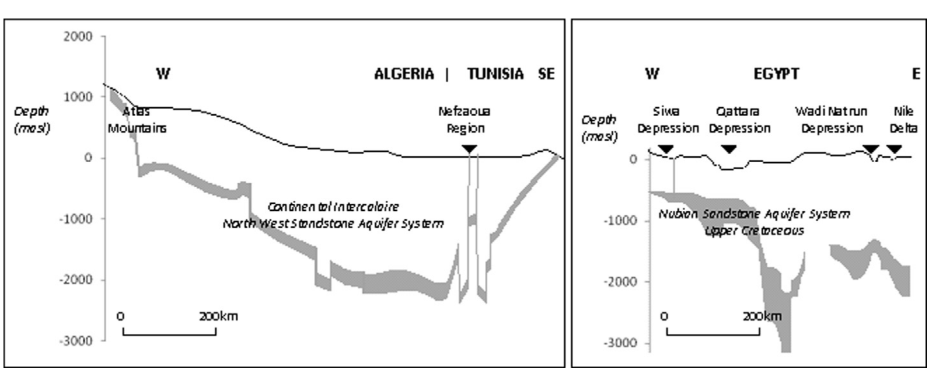

Fig. 2. Deep aquifer systems emerging at study areas (simplified from Edmunds et al., 2003; Sundborg and Nilsson, 1985).

upconing of saline under-layers or potential movement of fresh–salt interfaces, leading to saline intrusion have also been suggested in both regions (see e.g. Pallas, 1991; Zammouri et al., 2007). Close to the Nile Delta, salinization processes have been considered to justify the diversion of water from the Nile in order to recharge depleted groundwater supplies (Attia et al., 2005).

Socio-economic factors, including changing local institutions, and external economic drivers are recognized to play a role in driving changing irrigation practices and salinization processes in both regions (for more detailed discussion and analysis, see: King and Salem, 2012; King, 2011).

4. Materials and methods

4.1. Detecting changes in land cover

Analysis of satellite images using the Normalized Difference Vegetation Index (NDVI) (after Rouse et al., 1973; Tucker, 1979) has been demonstrated as a globally applicable measure for discriminating between vegetated and non-vegetated land covers. In arid environments, where rainfed vegetation is sparse, irrigated areas show a much higher level of vegetation cover, and therefore a higher NDVI signal. This method can be used for differentiating between irrigated and non-irrigated areas (see e.g. White, 2007). Recognized limitations include failure to differentiate between barren land, temporarily fallow, or immature crops that produce sparse vegetation cover (Huete and Jackson, 1987). Also, where vegetation is affected by salinization, a reduction of NDVI is observed (Alhammadi and Glenn, 2008).

285 Landsat Thematic Mapper (TM) images of the selected study areas at 30 m resolution were identified in the online database of the US Geological Service (USGS), covering the period 1984–2003, in the Western Desert, and continuing to the present for Southern Tunisia. Also, 435 Enhanced Thematic Mapper Plus (ETM+) images at 30 m resolution were identified, covering the period 1999-present for both regions (although from 2003-present a fault in the scan line corrector obscures some of the pixels). Image sets taken in comparable months were selected for each study area in order to minimize the possible effects of seasonal variations (Table 1). In the case of Nefzaoua, which receives higher winter rainfall than the Western Desert, images taken during the months of July and August were selected.

An additional global dataset was obtained from the Global Inventory Modeling and Mapping Studies (GIMMS) through the University of Maryland Global Land Cover Facility. GIMMS contains Normalized Difference Vegetation Index (NDVI) data for 1982–2006 at 8 km resolution. This dataset is not atmospherically corrected, and is more coarse than the Landsat data, but provides a higher (bimonthly) frequency. The dataset is derived from imagery obtained from the Advanced Very High Resolution Radiometer (AVHRR) instrument onboard the NOAA satellite series 7, 9, 11, 14, 16 and 17. The dataset has been corrected for calibration, view geometry, volcanic aerosols, and other effects not related to vegetation change. Use of high temporal frequency data such as the GIMMs dataset enables smoothing of seasonal effects and anomalies, and has therefore been used for recent land degradation and desertification assessments (e.g. Helldén and Tottrup, 2008).

Simple rectangular areas of 48 × 72 km were identified in each Landsat image, and NDVI was analyzed in each pixel. Using ERDAS Imagine™ software, the NDVI values were classified through an unsupervised iterative clustering process into two clusters of highest NDVI, representing vegetated areas, and lowest NDVI, representing non-vegetated areas.

The results were inspected visually to determine whether the areas identified were consistent with other available information from each time period on the location of lakes and cultivated areas, including agricultural development statistics previous scientific and technical accounts and higher resolution images available in Google Earth. A comparison of results obtained from the classification of images taken in the same place and time period by two different sensors (TM and ETM+) indicated that results for the study area as a whole were similar (less than 10% difference) (Table 2). In the case of Siwa, the presence of drainage lakes with very low NDVI values disrupted the classification. It was therefore necessary to introduce a third class in this case to accommodate the waterbodies.

Change detection was performed between successive Landsat 5 TM images from each location 1987–2003, and also between the series of Landsat 7 ETM+ images 1999–2009 in order to pinpoint areas where vegetation had been gained and lost. Using ERDAS Imagine™, changes (positive or negative) of 10% or more in the NDVI value were highlighted.

For the GIMMS AVHRR dataset, 27 pixels around the same cultivated areas of the Nefzaoua, and on each side of the Western Desert at Siwa and Wadi El Natrun were selected for analysis. An annual average was taken from the 24 bi-monthly NDVI values assigned to each selected pixel for each year. These were averaged across each area to obtain a single annual value for NDVI from each region. Within each region, several pixels were then selected for further analysis and plotted separately.

4.2. Comparison of land cover changes to other datasets

National archives containing data on rainfall, soil and water salinity were consulted, and available time-series datasets obtained. For the Nefzaoua region, published statistics included climate records covering the period 1981–2006 from the Kebili,

Table 1
Selected USGS Landsat scenes of study areas.

		TM	ETM+
Nefzaoua	Landsat	5	7
	WRS	2	2
	Resolution (m)	30	30
	Path Number	191	191
	Row Number	37	37
	Dates	11 July, 1984	
		21 August, 1987	
		24 August, 2003	
		04 August, 2010	
Siwa	Path Number	180	180
	Row Number	40	40
	Dates	11 October, 1987	7 November, 2000
		23 October, 2003	15 October, 2009
Natrun	Path Number	177	177
	Row Number	39	39
	Dates	26 August, 1984	12 August, 1999
		18 July, 1987	
		30 July, 2003	24 September, 2009
		16 September, 2003	

Table 2
Comparison of % classes in WRS-2 Path 180, Row 4 Landsat 5 TM (23/10/2003) and Landsat 7 ETM+ (16/11/2003).

	48 × 72 km area		8 × 8 km pixel 2		8 × 8 km pixel 3	
	Landsat 7 ETM+	Landsat 5 TM	Landsat 7 ETM+	Landsat 5 TM	Landsat 7 ETM+	Landsat 5 TM
Class 3 (Cultivated Area)	1.65	1.77	15.50	16.69	18.65	18.91
Class 1 (Lake)	1.91	1.65	26.94	25.80	18.65	12.76
Class 2 (Other)	96.44	96.58	57.56	57.51	62.70	68.33

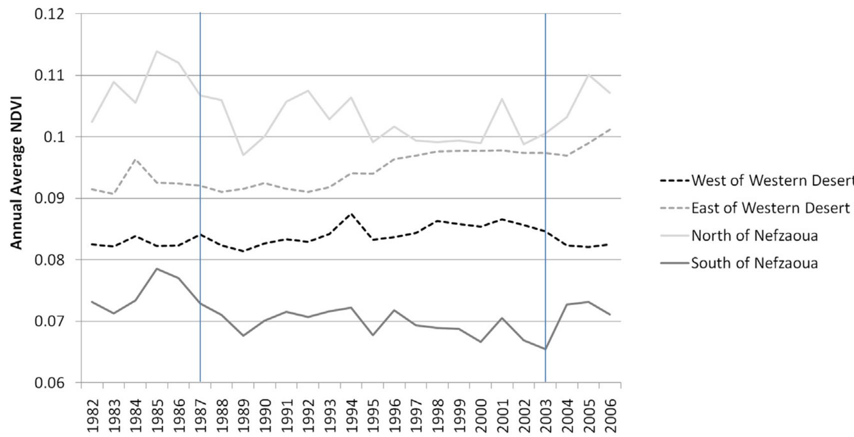

Fig. 3. Annual Average NDVI from bimonthly GIMMS AVHRR, 1987-2003.

Douz and El Faouar meteorological stations (DGRE, 1982-2006) were compiled. The spatial distribution of Total Dissolved Solids (TDS) levels from publicly monitored wells (DGRE, 1979-2006) was compared to the land cover change maps in ERDAS Imagine™. Temporal trends in the records of TDS at selected wells from each part of the region were plotted and compared using Excel (DGRE, 1998-2006). Public statistics held at the Regional Agricultural Development Commission (CRDA) on the extent and productivity of cultivated areas, groundwater extraction and groundwater quality in Nefzaoua over the period 1979–2004 were also analyzed. No further field datasets were sought in this case.

In the Western Desert of Egypt, all water-related datasets, including those for climatic data were difficult for researchers to access during the period when the archive visits were made (2008–10). Daily climatic data, 1958-present from the US National Oceanic and Atmospheric Administration (NOAA)[2] was consulted. The archives of the Egyptian Desert Research Center and the Ministry of Water Resources and Irrigation (MWRI) confirmed that the national programme for monitoring groundwater quality had been established more recently than the Tunisian one. Technicians of the MWRI were accompanied during field activities in Wadi El Natrun and Siwa, and data from monitoring over the period 2009–10 were obtained and analyzed with their assistance. Local farmers also provided some records of water quality analyses from their wells over additional recent years.

Although these available datasets were too sparse and brief in duration to enable the identification of any spatial or temporal trends, additional well inventories and accompanying chemical analyses have been published through a number of graduate theses (e.g. Abd El-Rahman Aly, 2007; Gad, 1999; Hossary, 1999; Ibrahim, 2005), but are not monitored continuously. Where previous datasets were georeferenced, they were entered to a Geodatabase in Google Earth and updated using a simple handheld conductivity meter. Semi structured interviews were carried out with cultivators at these locations.

Questionnaire surveys were also implemented in each region to obtain information on environmental changes (King and Salem, 2012; King, 2011). A total of 120 farmers and their households were interviewed. Questionnaires addressed land and water use practices, observation of rising or falling water tables and changes in water quality including salinization. Interviewees were also asked for their opinions concerning the causes and processes of salinization. Local farmers also provided some records of water quality analyses from their wells over recent years. The results were added to the geodatabase in Google Earth, enabling spatial analysis and comparison between the different datasets.

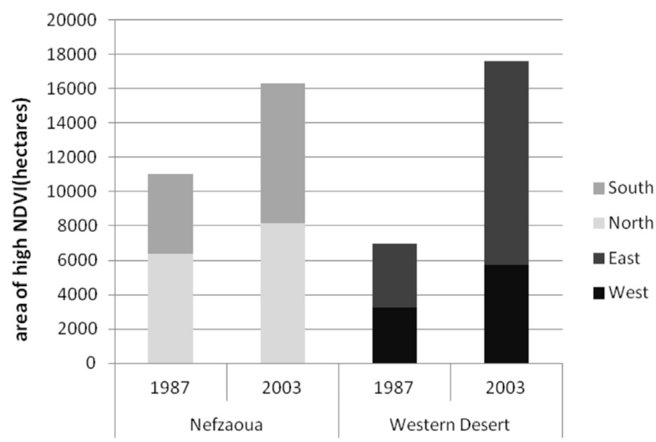

Fig. 4. Increase in high reflecting NDVI areas from Landsat 5 TM, 1987–2003.

5. Results

5.1. Inter-regional comparison of expanding irrigated areas: overview

Over the period 1984–2006, it is notable that average annual NDVI observed using the coarse resolution GIMMS AVHRR datasets fluctuated from year to year, and did not increase proportionally to the extent of the irrigated high NDVI areas (Fig. 3). Considerable intra-annual variations were also visible in this dataset (not shown in Fig. 3). There was a 17% rise in the average NDVI value in the AVHRR dataset for the Nefzaoua region. Published annual rainfall from weather stations located across Nefzaoua fluctuated, but showed no overall increase over this period.

The overall increase in the area of high reflectance vegetation in the Nefzaoua 1987–2003 detected using the TM image series was 51%. In the Western Desert, areas of high NDVI increased from 3263 ha in Siwa and 3707 ha in Wadi El Natrun in 1987–5734 ha and 11,869 ha in 2003.[3] The combined increase was

[2] http://gis.ncdc.noaa.gov/map/gsod/.

[3] since areas of young or sparse vegetation would not have been detected, these figures represent a conservative estimate of the cultivated area, but the best available assessment of the productive area.

therefore 153% (Fig. 4). However, considerable spatial and temporal variations were apparent within both cases.

5.2. Tracking salinization in irrigated areas of Nefzaoua, Southern Tunisia

Over the most recent decade (late 90s–2000s), a slower trend in the increasing extent of high NDVI irrigated areas is apparent. This has been associated with the effects of degraded land and water quality caused by salinization (OSS, 2003; Zammouri et al., 2007). Analysis of the spatial distribution of land cover change showed that more vegetation losses affected the north than other parts of the region (Fig. 5). Both land users and published statistics indicate that the groundwater table has fallen, increasing water scarcity and pumping costs. Groundwater quality, as recorded in the official monitoring results, has deteriorated somewhat in this region, possibly due to upwelling of more saline water from the CI (see El Fahem, 2003). The mix of different degradation processes resulting from these effects on groundwater availability and salinity may explain some of the observable land cover changes in the north.

The most rapid and extensive growth was in the southeast, in the Delegation of Douz (Fig. 5). The groundwater of the CT increased in salinity fastest in this area, rising from around 6 g/l TDS to above 8 g/l TDS over the period 2000–2005 at El Hsay and from 4 to 6 g/l at Bou Hamza. In this region, backflow of drainage water has been observed as a significant process affecting water quality, due to drainage conditions around El Hsay (e.g. El Fahem, 2003).

Surveyed cultivators from different parts of the region described problems due to increasing salinity, and also to scarcity of water occurring over this period. Survey results recorded infrequent irrigation water applications. Losses of productivity in *P. dactylifera* L. and the death of other fruit and vegetable crops were described and corroborated with local productivity statistics. Cultivators blamed malfunctions in the water distribution systems, the age of their wells, and the generalized scarcity of water for these problems. However, interviews also revealed that economic factors influence their salinity management practices. New opportunities in sectors other than agriculture, weighed against falling international date prices, may have affected investments of labor in water management and soil improvement.

5.3. Tracking salinization in irrigated areas in the North Western Desert, Egypt

Overall increases in the extent of the high NDVI area visible in the Landsat images continued, but since the late 90s there were losses in some areas, as well as continuing gains in others. Over the period 1984–2003, vegetation productivity losses observable in Landsat 5 images seem to be spread across the region. But in the higher resolution 1999–2009 Landsat 7 dataset, it could be observed that vegetation losses were particularly concentrated in the old cultivated lands at the center of the Wadi Natrun depression, while increases in the cultivated land continued to accelerate in the surrounding area (Fig. 6). What appeared from this new analysis was that degradation might be affecting productivity on the smaller, older farms in this area more than it was affecting the larger, newer farms. According to the farmers on the small farms, their greatest concern was most often not salinity (Electrical Conductivity in their wells remaining under use varied from 1 to 5 dSm (1–5000 $\mu S/cm^{-1}$), with a mean value of 2.5 (2500 $\mu S/cm^{-1}$)), but the falling water table. This reduces their access to water, thereby impairing their options for managing salinity increases, unless they can afford to pay the cost of deeper drilling and pumping.

Water users monitor and observe water quality continuously as it is applied and affects their crops. Farmers interviewed in Wadi El Natrun described a high degree of natural variation in levels of salinity occurring within a relatively small geographical area. For example: in one case two wells were dug at the same time, to the

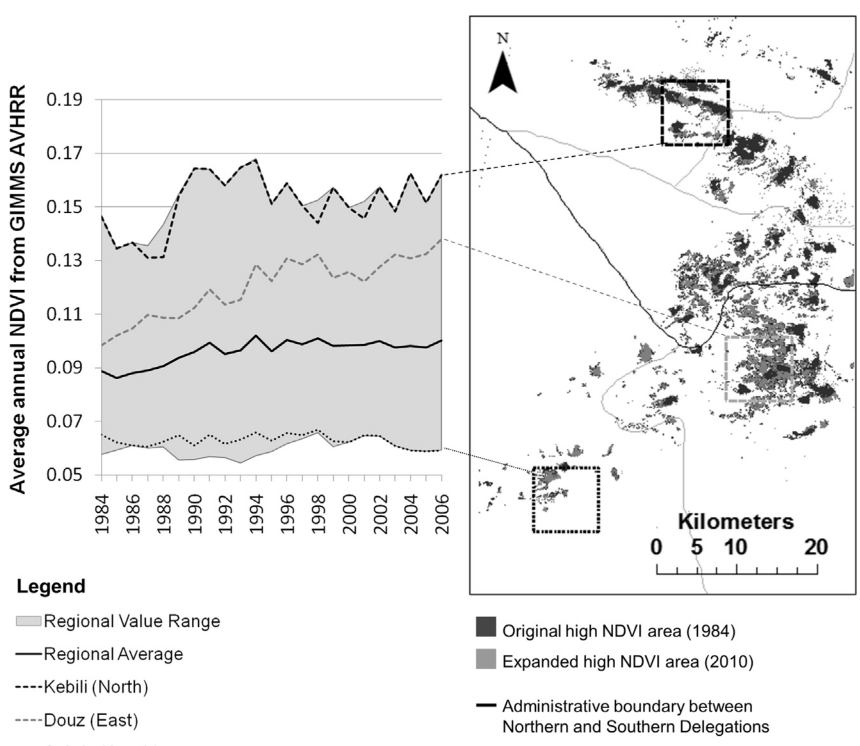

Fig. 5. Trend in GIMMS AVHRR 1982–2006 and high NDVI areas 1984–2010 in the Nefzaoua region.

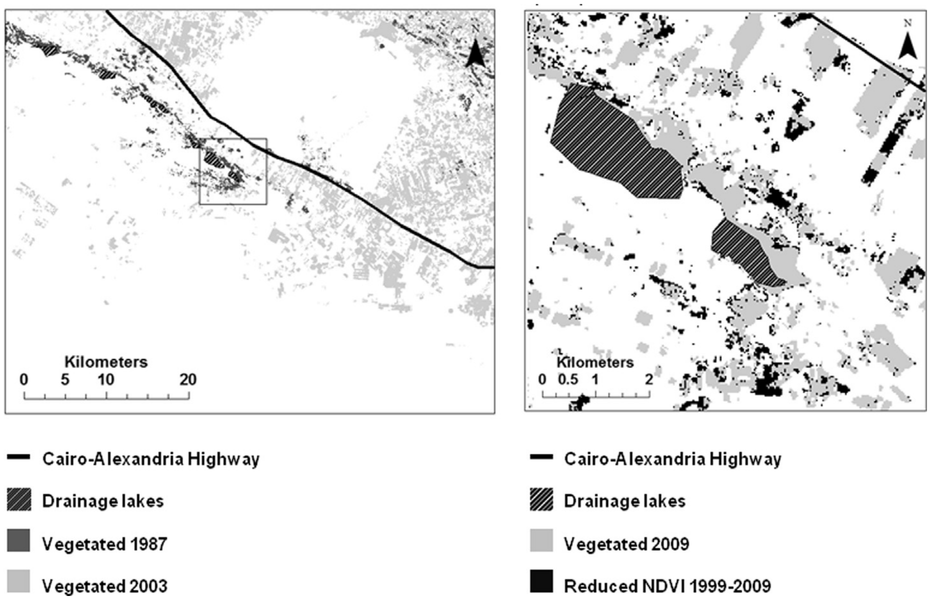

Fig. 6. Land cover change analyses in Wadi el Natrun, Eastern Side of North Western Desert, Egypt.

same depth, 10 m apart. One was too saline to use, the other was fresh. Where salinity cannot be managed, wells are simply abandoned. On large farms in the area, employees could recall a large but unquantifiable number of wells that had turned saline and been replaced over recent years. No records are kept when this occurs. Monitoring wells still in use will not record or explain where and why others turn saline.

Further to the West, in Siwa, on the other hand, water-logging was clearly taking place, as in the accepted interpretation of salinization processes described in Section 3 (see also Masoud and Koike, 2006). This is visible in the NDVI images as an expansion in the low NDVI lake areas at the center of the depression (Fig. 7). However, during semi-structured interviews conducted in the field, cultivators said that deep wells were also affecting water quality and pressure in neighboring springs, traditionally used for irrigation. The evidence from resampling of the wells where data on salinity was available over a ten year period confirmed increasing salinity levels at these locations e.g. from 4–7 dSm (4–7000 μS/cm^{-1}) in 2009 at Lehrek Spring and from 4–9 dSm (4–9000 μS/cm^{-1} at the neighboring Shaker Well over the period 1998–2009).

Re-analysis of higher resolution satellite images confirms that vegetation loss was not located only in low-lying areas likely to be affected by water logging, as indicated in previous investigations, but has also been taking place at higher elevations. This, together with the results from available water quality sampling confirms local farmers' theories of another explanation for the salinization process – i.e. hydrogeological change caused by increased groundwater extraction. However, given the notably elevated salinities recorded in some of the wells and springs in this area, it appears surprising that more degradation has not taken place in the cultivated area. One possible reason for this, observed through the interviews with cultivators, is the highly developed state of local knowledge concerning techniques for cultivation under saline conditions.

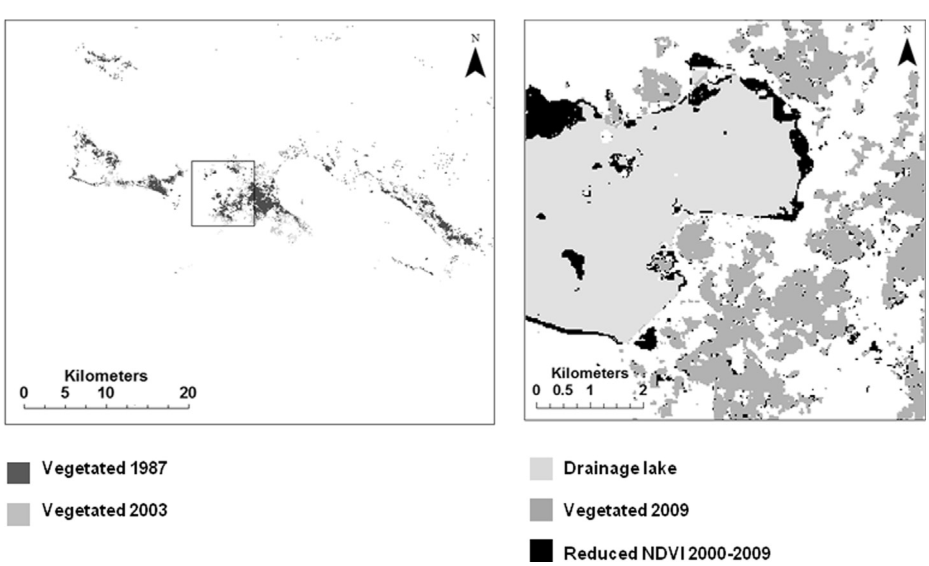

Fig. 7. Land cover change analyses in Siwa, western side of North Western Desert, Egypt.

6. Discussion

6.1. What insights for improved assessment of salinization threats have been enabled through the increased availability of materials and methods for land cover change detection?

There is a need to weigh land and water use decisions carefully throughout the drylands using well-adapted scientific methods to assess and manage degradation threats, including those associated with irrigation and salinization. The land cover geodatabase enables the location of areas where increases in water use for irrigation are taking place, and could also significantly improve the accuracy of national and regional assessments of present and future resource availability and degradation threats.

Since the United States Geological Survey (USGS) released the Landsat image archive for public use (http://edcsns17.cr.usgs.gov/EarthExplorer/) in 2008, the simple analyses used in this paper have become low-cost, and the resolution, frequency and range of spatial and temporal scales at which such analyses can be drawn are continually improving. As researchers continue to progress the use of these methods, including necessary adjustments for rainfall or irrigation where applicable, it may, in time, be possible to integrate such localized analyses within ongoing global assessments of irrigated areas (Thenkabail et al., 2009) and land degradation, including salinization (e.g. Bai et al., 2008; Helldén and Tottrup, 2008).

At 30 m, the resolution of the freely available images is still too coarse to be used in isolation to pinpoint degraded areas and to identify potential salinization processes. It is also to be hoped that in due course higher resolution satellite imagery could also become freely available to researchers in developing countries. To address this uncertainty in the meantime, this paper has demonstrated that remote sensing datasets can be effectively combined with other available information, including groundtruthing observations, time series analyses of water quality and socio-economic data. This approach is very much in keeping with the new conceptual approach to understanding the condition and dynamics of human environment systems (Reynolds et al., 2007; UNCCD, 2009). The approach has potential relevance for many dryland areas of the world, where data availability is poor, and interpretation of apparent degradation trends is needed.

In each case explored, the integration of remote sensing data with other available sources of local information enabled a revision of the prevalent views of salinization processes. While the overriding concern highlighted through all analyses remained focused on the long-term overextraction of groundwater, leading to and exacerbating the effects of salinization, through closer observation of spatial and temporal changes in vegetation cover together with other datasets, these effects were attributed to a more complex and nuanced range of causes and localized salinization processes. In addition to improving available assessments, this analysis can help to design more cost-effective monitoring and modeling efforts, or to prioritize investments in higher resolution images, if desired.

6.2. How do these insights connect to other ongoing national and scientific efforts to monitor, model and assess land salinization and degradation trends in the two selected cases?

In assessing salinization and degradation, several layers of complexity that decision-makers must consider are introduced in this paper. First, there is the need to monitor levels of salinity, to identify increases, effects on and threats of desertification (Geist, 2005). The new conceptual approach gives recognition to possible non-linear effects that may add complexity to efforts to monitor and assess the salinization process. In addition, we have observed that human innovation can reverse degradation and salinization processes, or find alternative ways to sustain and increase productivity where there is sufficient economic interest to do so. Our selected cases illustrate this point, by demonstrating surprising levels of productivity, even under highly saline and water-depleted conditions. Local and national decision-makers are therefore faced with the challenge to interpret these processes and management options in each particular context.

Integration of socioeconomic data (e.g. concerning trends and projections for growth in the local population and sectors of economic activities) is essential to enable a comprehensive assessment of resource management, including non-agricultural land and water uses (e.g. in industrial, domestic, and tourism sectors) that are not necessarily visible through satellite imagery alone. National census datasets available in the study areas have enabled this to be done on a regional scale in the selected study areas (e.g. Attia, 2002; MARH, 2006). Whether through national census data, or other purpose-designed surveys, as demonstrated in this investigation, sub-regional socio-economic data can also be useful.

Scarcity of environmental data is a common challenge in many arid environments, including those under study (see previous studies e.g. Masoud and Koike, 2006). This paper has demonstrated an innovative approach to overcoming data-scarcity. However, we have also observed that there is not an absolute scarcity of data on salinity in soils and water in either of the study areas. As demonstrated in this, and many previous investigations, land and water users are aware of changes affecting their resources (see e.g. Lightfoot et al., 2009), and use ecological management techniques where they can to mitigate these changes. In this investigation, it was also observed that monitoring including chemical analysis of water and soil qualities is conducted privately by well owners, but that the information is not publicly collated and analyzed. Individual land and water users cannot effectively conduct wider systems analyses of degradation trends and management alternatives unless they collaborate to build and use regional datasets.

Some public databases are beginning to incorporate privately generated data. In Egypt's Western Desert, for example, data generated by users for well permit applications is stored electronically. However, such approaches have not yet been connected to public assessments of land and water quality and productivity. The land cover geodatabase provides a coherent temporal and spatial frame within which scattered local datasets could be collated for analysis. Periodic analysis and publication of this information in accessible and durable formats could enhance its availability and use by scientists and decision-makers undertaking environmental impact assessments. In order for this to be achieved, it would be necessary to overcome a notable degree of expert skepticism regarding participatory monitoring approaches, and a lack of interest amongst private farmers to make data on their land and water available for public use.

7. Conclusions for international scientific efforts to contribute to the monitoring of land degradation in arid regions under threat from salinization

The global scientific challenge to monitor and manage salinization effects in irrigated arid areas increases every day with the growing extent of irrigation systems. Recent global investigations of land degradation (Bai et al., 2008; Helldén and Tottrup, 2008) have not yet addressed the possible effects of irrigation in temporarily increasing productivity, or the consequences of these increases, where they are already resulting in degradation (Kijne, 2003; Thomas and Middleton, 1993). This paper has demonstrated the integration of a range of simple and accessible methods enabling assessment of the extent and ecological processes of salinization in the two selected cases in the Northern Sahara to better inform effective local management responses and global scientific assessments.

The approach to overcoming paucity of data that is demonstrated in this paper is considered likely to be of relevance to scientists in the case study areas and also to scientists who are interested in global scientific assessments of salinization, including these areas. However, it is important to reiterate and underline that the remote sensing techniques are not used in isolation, but rather in combination with other local and national datasets. Supplementary data and analysis needed to accompany the land cover datasets will vary with context, depending on the different biophysical and socio-economic drivers at play in the salinization processes.

The present global extent and significance of the irrigated areas, and the range of options available for assessment and management of salinization and other threats, were not conceived of when scientific and technical responses to environmental degradation in the drylands were first outlined for the UNCCD over twenty years ago. Until now, it has been impossible to consider comprehensive regional approaches to prevent salinization, or to determine who might or might not pay the costs to reverse this or other land degradation processes. However, proponents have argued that the emerging tools of dryland development science could change this situation.

Our study revealed that use of the new conceptual and methodological approaches implied needs for a new level of public coordination to convene, compile, house and periodically publish assessments and associated datasets for scientific use and posterity. In light of this, a review of the anticipated roles and capacity needs of public authorities and other stakeholders in enabling and ensuring effective public scientific assessments of land and water resources, and identifying appropriate management responses to degradation problems might be warranted.

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