SPATIAL ANALYSIS OF AGRICULTURAL LAND USE CHANGES IN THE KHABOUR RIVER BASIN OF NORTHEASTER SYRIA

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ABSTRACT

The Khabour River, southernmost tributary to the Euphrates, is a case study in the complexity of managing riparian resources. The river is located entirely within Syria but the watershed includes portions of Turkey and Iraq. Indeed, on account of the steep southward precipitation gradient in the region, the spring-fed Khabour is recharged almost exclusively by precipitation that falls on Turkish soil. For millennia the northern portions of the Khabour watershed have been used for rainfed agriculture. Until recently, however, cultivation along the dry southern stretch of the river was limited to the floodplain, where traditional gravity methods of irrigation could be practiced. In the last half of the 20^{th} century irrigation initiatives in both Turkey and Syria fundamentally altered the human and hydrologic character of the watershed. First came broad introduction of the diesel-powered pump, which allowed farmers to draw on deep groundwater reserves from virtually anywhere in the basin. Next came major impoundment and diversion schemes. In the 1990s alone two major dams were constructed along the Khabour and plans to import water to the Turkish portion of the basin neared completion. We have used paired Landsat TM images from September 1990 and 2000 together with ASTER-derived digital elevation data and the statistical tools of landscape ecology to quantify changes in the distribution of irrigation projects in the Khabour watershed. Through these analyses we can describe the changing character of agriculture in this region, and by integrating this remotely sensed data with biophysical information on climate and hydrology it is possible to evaluate the hydrologic impact of various water extraction and diversion schemes.

INTRODUCTION

The climate of northern Mesopotamia is characterized by a strong north-south precipitation gradient. The mountains of Turkey and northern Iraq can receive in excess of a meter of rain per year while the Euphrates Plain of Syria and Iraq average little more than 100-mm. The climatological limit of dryland agriculture—the line south of which which no crop can be cultivated without supplementary irrigation in an average year—lies somewhere between the 200-mm and 300-mm isohyets, depending on local evaporation demand (Brichambout and Wallen, 1963). In northeastern Syria this line runs east to west across the Jezireh steppe, the area north of the Euphrates River, and crosses into Iraq below the Jebel Sinjar anticline (Figure 1). The line bisects the basin of the Khabour River, southernmost major tributary to the Euphrates system, into a northern portion, where rainfed agriculture is possible, and a southern portion, where all crops require irrigation. Even north of the rainfed limit irrigation is commonly practiced in the cultivation of summer crops and as a supplement to precipitation for certain winter crops (USDA, 1982).

For a large portion of the Khabour Basin, then, access to a reliable source of water is the key ecological constraint to agriculture. Such is the case throughout much of the Middle East (Hillel, 1994) and in semi-arid and arid zones throughout the world (Gleick, 1993; DePauw et al., 2000). The critical role of water in the emergence and succession of early Mesopotamian civilizations is well-documented in the archeological record, in which major human migrations and urban origins can be associated with hydrologic instability (Hole, 1994), and in the legends and laws of Sumer, Babylonia, and the Hebrew Bible (Hillel, 1991). Then, as now, the distribution of water in the arid to semi-arid landscape was highly correlated with the distribution of agriculture and, to a high degree, the distribution of the human population (Li et al., 2001).

The effective distribution of any ecologically limiting resource, however, is defined by human technologies as well as by natural conditions. Chemical fertilizer, for example, has enabled the expansion of intensive agriculture into zones with nutrient-limited soils, effectively changing the distribution of high potential agricultural lands. Similarly, water diversion and desalinization schemes currently support urban centers in desert regions of Saudi Arabia and the Southwest United States that have virtually no natural carrying capacity for humans (Gleick, 1993). Technological innovation in the access to water has played a fundamental role in the agricultural development of the Euphrates River system as well. From traditional gravity irrigation to diesel-powered extraction of groundwater to grand impoundment and diversion schemes humans have accessed and manipulated the region's hydrologic resources in a manner that has had profound historical (Hole, 1994), economic (Bilen, 1994), political (Gruen, 1999), and environmental (Kolars, 1994) consequences. The implementation of new hydrologic technologies can lead to improved water efficiency and international cooperation (Gruen, 1999) but more often it has led to unforeseen resource degradation (e.g. Hoogeveen et al., 1999) and political conflict (AINA, 2000; Hillel, 1994).

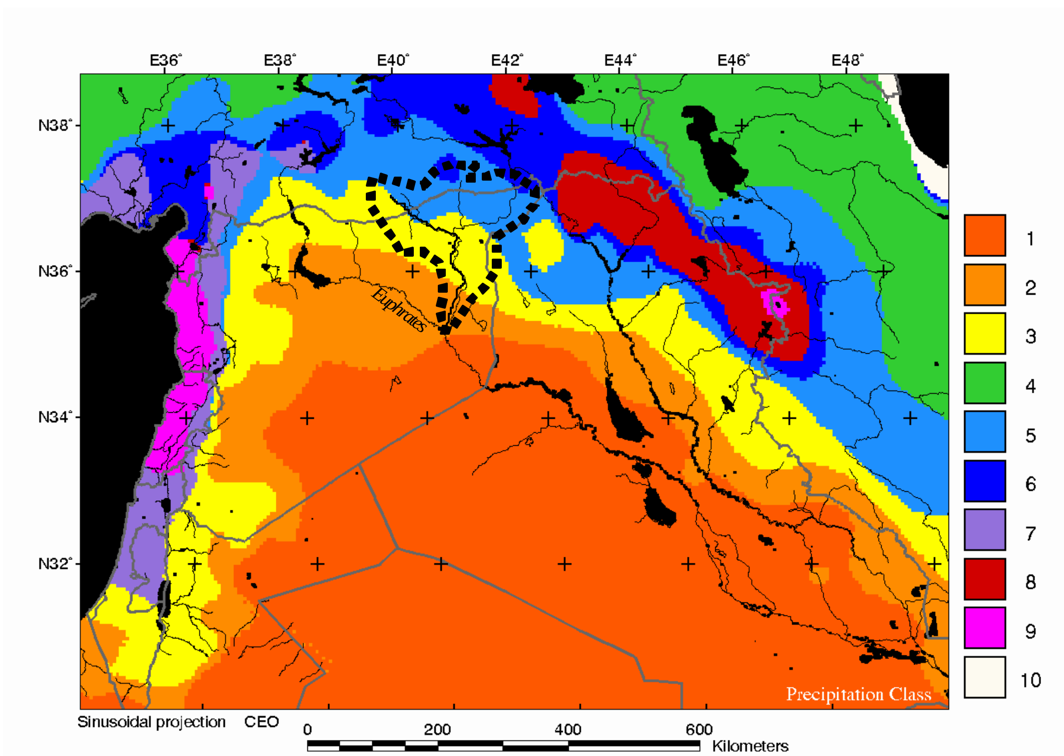
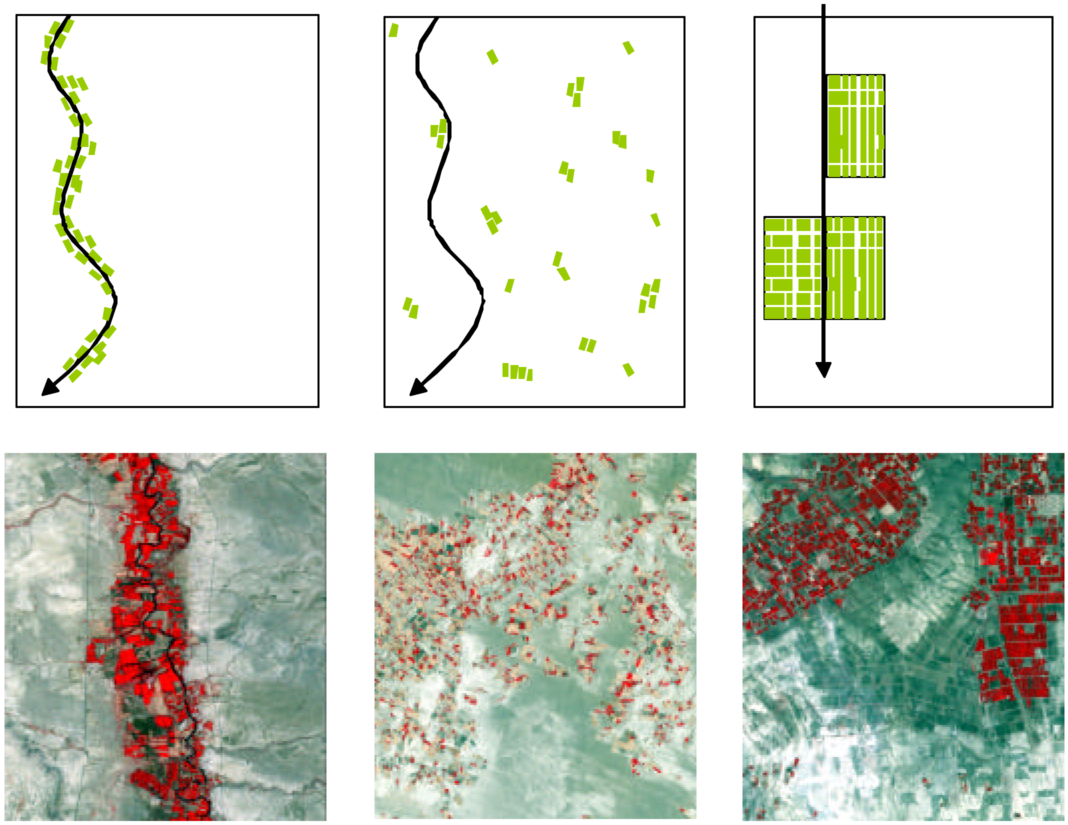


Figure 1: Multitemporal unsupervised classification of monthly precipitation data, demonstrating the strong north-south precipitation gradient in the Near East. The dotted line represents the outline of the Khabour watershed and the main course of the Khabour River is shown in bold. The limit of dryland farming roughly follows the border between Class 3 (yellow) and Class 5 (light blue).

Three methods of water withdrawal currently dominate irrigated agriculture in the Euphrates Basin: (1) floodplain irrigation, (2) groundwater extraction, and (3) canal irrigation (Figure 2). Combinations of the three are also observed. From the perspective of spatial distribution, floodplain irrigation represents the most "traditional" irrigation system. For thousands of years humans have practiced agriculture along the alochthonous rivers of the Middle East (Hillel, 1994). In the relatively flat floodplain crops can draw on the moisture of natural river floods, can be watered using small gravity-driven diversions and levee breaks, or can be irrigated to some distance (though little topographic rise) using low-power diesel and electric pumps. Under this irrigation regime agriculture is limited to the fertile valley that surrounds the river. Along portions of the main stems of the Tigris and Euphrates this area is quite extensive, but on the Khabour River the floodplain is on the order of 2 to 3-km across.



(A) (B) (C)

Figure 2: Schematic diagrams of expected field distribution under (A) floodplain, (B) groundwater, and (C) canal irrigation, with 4-3-2 false color TM images of examples from northeast Syria.

In the past century floodplain irrigation in the Euphrates has increasingly given way to irrigation by groundwater extraction. In this system more powerful diesel pumps are used to draw irrigation water from tens to hundreds of meters below the surface, servicing one or two fields at a time. In marked contrast to the floodplain system, irrigation by groundwater withdrawal does not require that farms be clustered around a surface water body; a dispersed distribution of farms may, in fact, be favorable in order to avoid local drawdown of the water table or depletion of an isolated aquifer. For the well irrigator the distribution of water is defined by hydrogeology rather than surface drainages, and the distribution of agriculture reflects this change. In the Khabour Basin and elsewhere groundwater irrigators have encountered problems with water quantity and quality. Sometimes all this means is that a well must be drilled deeper or in a different location, but in other cases limited or low quality irrigation reserves have led to secondary salinization of marginal agricultural soils (e.g., Hoogeveen et al., 1999; see also Ghassemi et al., 1995).

The third irrigation regime, impoundment and diversion to canals, requires centralized construction and planning. The canal network defines the location of irrigated fields, and these fields are generally packed closely together in order to minimize construction expense and water loss due to evaporation and leakage. Nonetheless there can be considerable water loss to evaporation off of shallow or poorly placed reservoirs, and leakage from poorly maintained pipes can undermine the intended benefit of the diversion scheme (Gleick, 1993). There are currently canals in place along the Lower Khabour but they are not active for summer irrigation. Both Turkey and Iraq have active canal irrigation schemes in or adjacent to the Khabour Basin.

The changing spatial character of irrigation in the Khabour Basin has important social implications. Lands traditionally used for grazing herds are now interrupted by islands of intensive agriculture, and groundwater withdrawals for agriculture in the steppe may well be responsible for lowering the regional water table to the point that the Lower Khabour now runs dry every summer—a phenomenon previously unknown in recorded history. Pumping in Turkey is blamed by some for diminished flow in the Ras-al-Ain spring at the head of the Syrian Khabour, while groups within Syria debate the impact of the nation's own diversion and pumping schemes on the health of the river (AINA, 2000). The biophysical implications can be subtler. For one, evaporation and transpiration rates may be greater on the hot and windy steppe then they are in the relatively sheltered, densely vegetated floodplain (Messing and Akrimi, 1998). The dispersed patterning of fields on the steppe might also impact evapotranspiration, as it is possible that vegetated fields increase the humidity and decrease the temperature of the surrounding area, causing water use efficiency or crop yields to be higher when fields are clustered than when they are distributed (McAneney et al., 1994; Philip, 1987). The move out of the floodplain also means a move onto soils not previously used for intensive agriculture. The salinization potential of gypsiferous soils in the area is substantial, and some of these soils suffer from loss of aggregate structure when wetted and subsequent susceptibility to wind erosion (Mousli, 1981).

In this paper we report on the first stage of our research on irrigation in the Khabour Basin: quantitative description of the spatial density and structure of the irrigated landscape. We consider all three defined irrigation regimes (floodplain, groundwater, and canal) at two points in time, September 1990 and September 2000. In the intervening decade there was considerable change in the extent and character of irrigated agriculture in the Khabour. Quantitative spatial analysis is prerequisite to any investigation of land-use change (Forman, 1995), and it provides a powerful foundation for assessing the role of water in the construction of the semi-arid agricultural envrionment (Li et al., 2001). Satellite imagery provides useful inputs for these analyses, and in the international, politically contentious watershed of the Khabour River it is a necessity (Beaumont, 1996).

MATERIALS AND METHODS

The Study Area

The Khabour River begins as a small stream in the Southern Anatolia region of Turkey, fed by rainfall and snowmelt from the Turkish highlands to the north. Shortly after crossing the Turkey – Syria border the stream grows substantially from the input of several major karstic springs (Burdon and Safadi, 1963). The river then flows southeasterly through the northern portion of the Syrian Jezireh before meeting the Jagh-Jagh River at the town of Hasakah (36^{o} 30' N, 40^{o} 45' E). Here the river turns due south and runs through the semi-arid southern Jezireh to its confluence with the Euphrates near Deir-ez-Zor (35^{o} 8' N, 40^{o} 25' E). The natural flow of Upper Khabour, gauged at Hasakah, is between 1.4 and 1.6 million $m^3\ yr^{-1}$ (USDA, 1982). In its course from the Turkish border to confluence with the Euphrates the Khabour transverses a strong north-south precipitation gradient. At the headsprings precipitation is generally in excess of 300-mm yr^{-1} (and the headwaters in Turkey can receive over 800-mm yr^{-1}). At the confluence annual rainfall is less than 150-mm.

For the purposes of this study we have selected a region of the Lower Khabour Basin (south of Hasakah) for which both Landsat TM data and ASTER-derived digital elevation models (30-m resolution) were available. This "Lower Khabour" study area (3,875-km^2) was subsampled for further analysis: the "Steppe" region (351-km^2), representative of expanding groundwater irrigation, and the "Floodplain" (116-km^2), a zone where floodplain irrigation nearly died between 1990 and 2000. There were no examples of active canal irrigation in the Lower Khabour region, so a portion (1,070-km^2) of the Harran Plain of Turkey—actually located just west of the Khabour Basin, in the watershed of the Balikh River—was used for the analysis of canal-based irrigation.

Image Processing

Landsat TM images covering northeastern Syria (Path 171 Row 35 and Path 172 Row 34) were acquired for September 2, 1990 and September 5, 2000 and georeferenced to the Yale University Southwest Asia Project (SWAP) Regional Mosaic. The TM NDVI index was then calculated in ERMapper image processing software (Earth Resource Mapping, San Diego, CA) and for each study region five reference pixels were selected representing bare soil or apparently unaltered structures. The reference pixels were used to establish an NDVI offset between 1990 and 2000 images (-0.04 from 1990 to 2000 in Path 171 Row 35 and -0.02 in Path 172 Row 34). Taking into account this calibration an NDVI value of 0.15 (+/- 0.05) was used to distinguish vegetated from unvegetated terrain. As the TM images were from early September, at the end of the dry Mediterranean summer, all vegetation in the fully agricultural Harran Plain and semi-arid Lower Khabour was assumed to be irrigated agriculture.

Thresholded NDVI images were exported to ArcGIS 8.1 (ESRI, Redwoods, CA) where hydrologic and topographic analyses were performed using a 30-m ASTER-derived DEM. Any raster cell with a contributing area greater than 10,000 cells (9-km^2) was classified as a zone of concentration for surface drainage. The thresholded images were also imported to FRAGSTATS 3.2 (McGarigal et al., 2002) for raster analysis.

Spatial Statistics

FRAGSTATS is a program designed to quantify landscape structure. For raster input the program can calculate more than 40 metrics at the patch, class, and landscape level. The “patch” is defined as a group of contiguous raster cells that has the same assigned grid value (e.g., an irrigated field), a “class” is the full collection of patches with a common grid value, and a “landscape” is the collection of all classes within a user-defined landscape boundary. This boundary was set separately for each analysis region. The metrics area (AREA), Euclidean nearest neighbor (ENN), and proximity (PROX) were calculated for each irrigated patch and as mean values for the region of analysis. AREA is calculated from a standard cell count. ENN is defined as the shortest straight-line distance from the edge of a patch to the edge of the closest neighboring patch. PROX is a measure of neighborhood field density, defined as:

$$PROX = \sum_{s=1}^{n} \frac{a_{ijs}}{h_{ijs}^{\ 2}}$$

Where a_{ijs} is the area (m^2) of patch *js* of class *i* within a specified radius (here set at 1000-m) of patch *j* of class *i*, and h_{ijs} is the distance (m) between patch *ij* and patch *ijs*, based on patch edge-to-edge distance, computed from cell center to cell center. Calculation of parameters in FRAGSTATS is dependent on raster resolution and scale of analysis, so care must be taken in making comparisons across data sources (McGarigal et al., 2002). It is also important to note that the limited resolution of TM data can obscure narrow divisions between fields. For this reason a FRAGSTATS-defined patch may comprise several neighboring fields that appear to be “touching” at 30-m resolution. This represents a problem if number of plots or size of farm is of interest, but from the biophysical/ecological perspective it is actually quite convenient: fields that lie within 30-m of each other do form a single ecological patch for many purposes, and most impacts of irrigation on microclimate or irrigation will be relevant at the scale of the patch, or field cluster, rather than follow strict field boundaries.

Total irrigated area, percentage of landscape in irrigation, total core area, and percent of irrigated area that is core were calculated on the class level. The core area of each patch was defined as all pixels that lay two pixel lengths (60-m) from the closest edge. Additionally, the FRAGSTATS metrics Patch Cohesion Index (COHESION) and Percentage of Like Adjacencies (PLADJ) were calculated for the class. These metrics of patch connectivity are redundant, but both are included here because cohesion is calculated on the FRAGSTATS-defined patch while PLADJ is calculated for each raster cell.

COHESION is a measure of the physical connectedness of patches within a single class, defined as:

$$COHESION = \left[1 - \frac{\sum_{j=1}^{n} p_{ij}^{*}}{\sum_{j=1}^{n} p_{ij}^{*} \sqrt{a_{ij}^{*}}} \right] \cdot \left[1 - \frac{1}{\sqrt{Z}} \right]^{-1} \cdot (100)$$

where p_{ij}^{*} is the perimeter (m) of patch *j* of class *i* in terms of number of cells, a_{ij}^{*} is the area of patch *ij* in terms of number of cells, and *Z* is the total number of cells in the landscape. The index ranges from 0 to 100, with larger values indicating greater clumping or aggregation of patches. The index is only sensitive up to a percolation threshold of patch concentration and may not be an effective measure for a spatially dominant class.

Where COHESION depends on FRAGSTATS identification of patches, PLADJ measures aggregation on the scale of the raster cell as a ratio of like adjacencies to total adjacencies per cell, based on a double-count method (i.e., cell p is adjacent to cell q and cell q is adjacent to cell p):

$$PLADJ = \left(\frac{g_{ii}}{\sum_{k=1}^{m} g_{ik}} \right) \cdot (100)$$

Where g_{ii} is the number of like adjacencies (joins) between pixels of patch type (class) i and g_{ik} is the number of adjacencies (joins) between pixels of patch types (classes) i and k. PLADJ ranges from 0 to 100, with 0 indicating maximum disaggregation and values increasing with increased aggregation of the class.

For all FRAGSTATS analyses presented here only two classes were defined: irrigated field and non-irrigated matrix. The definition of these classes was based on a single image for each season, so only fields active in the first week of September are represented in the irrigated class. Fields that were fallow at the time of the image are included in the background matrix. From the perspective of total land use, then, there is a systematic underestimate in the calculation of class level AREA, patch and class level PROX and ENN, and class level COHESION and PLADJ. For the study of certain biophysical issues, however, the distribution of active fields is actually of greater interest. Vapor pressure feedback and its influence on evaporative demand, for example, is a function of active field area rather than the total area in farms.

RESULTS AND DISCUSSION

In the Lower Fields analysis region of the Khabour Basin there was a drop in total active irrigated area between September 1990 and September 2000, from 7,167 to 6,222 hectares (Table 1, based on NDVI cutoff of 0.15). Allowing for an uncertainty of +/- 0.05 in the NDVI threshold, the irrigated area in 2000 was between 6,259-ha and 8,135-ha and the irrigated area in 1990 was between 5,355-ha and 7,157-ha. The drop in irrigated area was expected, as agriculture in the southern portion of the basin generally declined during the 1990's while agriculture along the Upper Khabour expanded dramatically (data not shown). The loss of irrigated area in Lower Fields was driven by a drastic loss of farmland in the Floodplain, from 3,719-ha in 1990 to 627-ha in 2000. Irrigation farming outside of the floodplain actually increased during the 1990's; in the region that we analyzed there were 823 irrigated ha in 1990 and 1,943 in 2000. In both 1990 and 2000 the Lower Fields region was sparsely cultivated. Our figure of less than 2% coverage by irrigation is an underestimate from the perspective of total land use (see Methods), but even accounting for fallow cycles no more than 5% of the area was being used for summer irrigation in either year. In the floodplain irrigation was quite dense in 1990 (over 32% of the landscape in active fields) but by 2000 density of active irrigation in the floodplain was no greater than density of active irrigation in the steppe.

Table 1: Extent and spatial structure of active irrigation, September 1990 and September 2000.

Region of Analysis	Year	Total Landscape Area (ha)	Total Irrigated Area (ha)	% of Landscape Irrigated	Mean Patch AREA (ha)	Mean Patch ENN (m)	Mean Patch PROX	Total Core Area (ha)	% of Irrigated Area That Is Core	Patch Cohesion	% Like Adjacencies
Lower Fields	1990	387515.00	7167.24	1.92	26.75	170.29	23.66	1262.07	17.61	90.22	75.12
	2000	387515.00	6222.33	1.61	4.59	185.66	3.12	477.72	7.68	80.68	68.74
Steppe	1990	35078.13	822.51	2.34	7.66	215.24	8.69	78.48	9.54	87.10	75.85
	2000	35078.13	1942.92	5.54	6.20	162.33	6.90	213.66	11.00	85.38	75.62
Floodplain	1990	11572.00	3718.98	32.14	42.05	78.47	72.92	924.21	24.85	93.94	79.63
	2000	11572.00	627.21	5.29	6.11	136.03	4.15	44.91	7.16	80.78	65.45
Harran	1990	107044.00	18132.21	16.94	24.70	149.89	426.95	9973.08	55.00	98.15	90.97
	2000	107044.00	70825.86	65.47	128.31	91.16	90038.78	49512.87	69.91	99.96	94.58

In the Harran Plain the 1990's saw a significant increase in irrigated agriculture. This intensification is associated with of the Turkish Urfa-Harran irrigation project, for which water from the Upper Euphrates Basin is diverted to the Harran Plain via the Urfa Tunnels (Beaumont, 1996). Total irrigated area in the portion of the Harran under study increased from 18,132-ha in 1990 to 70,826-ha in 2000, at which time more than 65% of the landscape was in active irrigation.

Mean patch AREA decreased between 1990 and 2000 in the Lower Fields Region, from 26.75-ha in 1990 to 4.59-ha in 2000, while mean patch ENN showed a slight increase (170.29-m to 185.66-m) and mean patch PROX decreased substantially (23.66 to 3.12). The change in AREA is not indicative of a trend towards smaller field size (Figure 3a), but rather reflects the influence of several extremely large patches formed by closely packed fields in the floodplain. By September 2000 field abandonment had caused these patches to become fragmented. Indeed, mean AREA in the Floodplain subregion decreased by a factor of nearly 7 between 1990 and 2000 while mean AREA in the Steppe subregion was virtually unchanged. The increase in ENN was also driven by changes in the floodplain, where mean ENN nearly doubled from 1990 to 2000. ENN in the Steppe for the same period decreased as a result of an increase in overall field density in that subregion. Similarly, the change in PROX in the Lower Fields region is driven by change in the floodplain. Fragmentation and loss of irrigated area in the Floodplain caused PROX to drop from 72.92 to 4.15 in that subregion while PROX in the Steppe remained relatively constant. For Lower Fields on the whole there is a patch-level trend towards lower PROX—and therefore relatively greater isolation of irrigated fields—between 1990 and 2000 (Figure 3b). In the Harran Plain mean patch area increased between 1990 and 2000 (24.70-ha to 128.31-ha) and ENN distance decreased (149.89-m to 91.16-m). The trend in both metrics is indicative of an increase in field density and aggregation. The PROX index calculated for the Harran Plain increased enormously between 1990 and 2000 (426.95 to 90,038.78), a result that reflects the dominance of irrigated agriculture in 2000 as well as the packing of fields around the canal system.

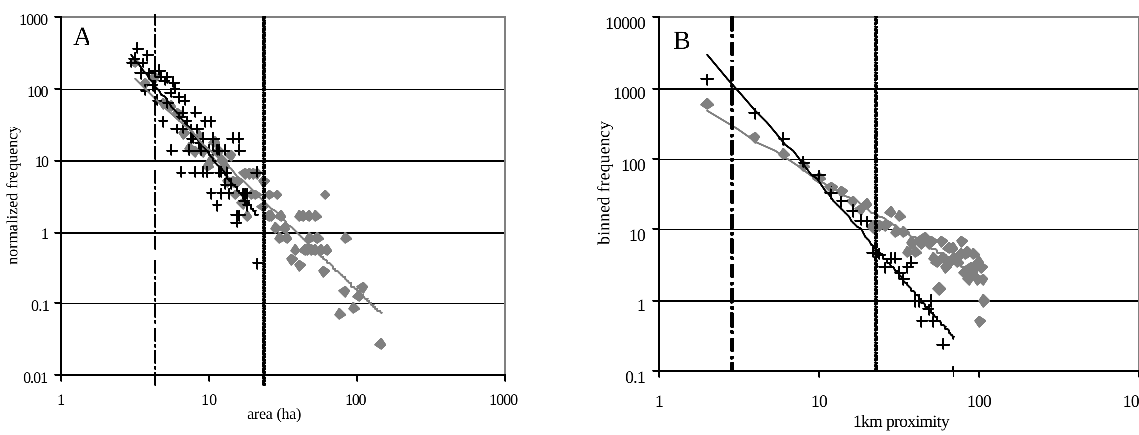


Figure 3: Lower Fields binned frequency for (A) AREA and (B) PROX in 1990 (?) and 2000 (+). Regression lines for AREA are indistinguishable between the two years, indicating that the change in mean AREA between 1990 (dotted line) and 2000 (dashed line) results from the loss of a large, low frequency patches rather than from a systematic transition to small field size. Regression for PROX, however, indicates a systematic shift to more isolated fields in 2000, as indicated by the greater magnitude of the regression slope.

The percentage of total irrigated area identified as core area is interpreted in this study as an indicator of both field size and field aggregation, on account of the limited resolution of analysis. In floodplain agriculture fields are highly aggregated along the river, forming a small number of large patches at 30-m raster resolution. The ratio of patch margin to total patch area is smaller for these extensive, multi-field patches than it is for isolated fields. Core area, therefore, accounts for a greater percentage of irrigated area in Lower Fields in 1990 (17.61%) than in 2000 (7.68%), and was high for Floodplain in 1990 (24.85%). There is evidence that in irrigated agriculture water use efficiency is lowest at the margins of fields, where the vapor pressure deficit tends to be most severe (Messing and Akrimi, 1998). This loss in WUE may result in greater evapotranspiration and/or a decrease in crop yield due to water stress and the partial closure of plant stomata (McAneney et al., 1994). In either case there is some advantage to limiting the exposed edge of irrigated patches in an arid environment. From this perspective the transition from floodplain to groundwater agriculture in the steppe carries a cost, while the transition to canal agriculture—percent core area was greatest of all for the Harran Plain in 2000—is beneficial.

Both COHESION and PLADJ were high for Lower Fields in 1990 (90.22 and 75.12, respectively), a product of similarly high values in the Floodplain (93.94 and 79.63). As floodplain agriculture declined and disaggregated the values of COHESION and PLADJ dropped for subregion Floodplain and for Lower Fields. The parameters held steady for subregion Steppe between 1990 and 2000, reflecting the generally non-aggregative nature of groundwater irrigation. Values for COHESION and PLADJ were high for the Harran Plain in both 1990 and 2000. PLADJ showed an increase from 1990 to 2000 for the Harran (90.97 to 94.58) as the canal system became fully active, while the COHESION parameter seems to have reached the percolation threshold for a spatially dominant class (McGarigal et al., 2002) and showed little change.

The transition from floodplain to groundwater-based irrigation in the Lower Fields study area can be documented in reference to topographic and hydrologic variables as well. The mean elevation of vegetated TM pixels within Lower Fields increased from 274-m in 1990 to 297-m in 2000 (Figure 4a) due to field abandonment in the floodplain and intensification on the elevated steppe. The transfer of production from the relatively sheltered floodplain to the exposed, windy steppe could have a significant impact on potential evaporation and yield from irrigated fields (Messing and Akrimi, 1998). Greater reliance on groundwater resources also loosens the correlation between the location of surface drainages and the placement of irrigated fields. Mean distance from an irrigated pixel to an area of concentration for surface drainage (i.e., a significant wadi or river) climbed from 480-m in 1990 to 702-m in 2000 (Figure 4b). This shift reflects a qualitative change in the way that farmers are gaining access to the ecologically limiting resource.

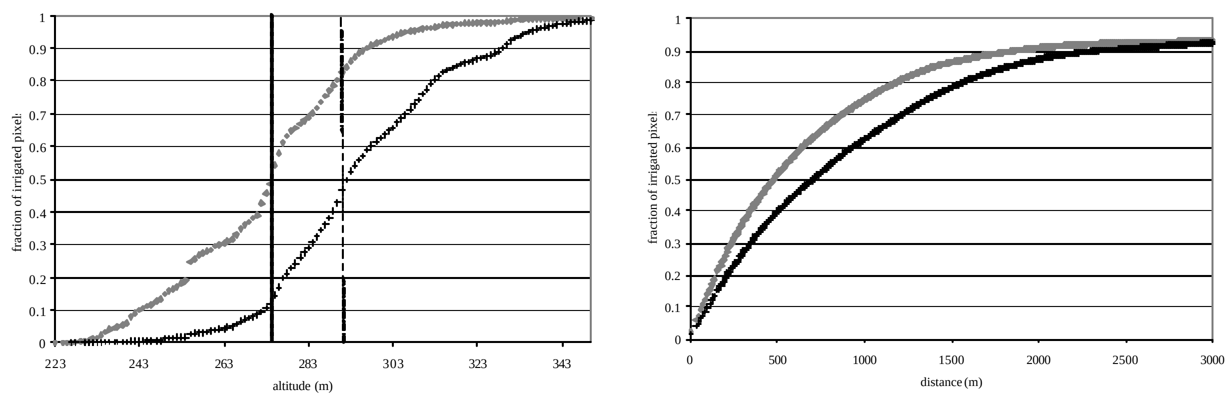


Figure 4: Fraction of irrigated pixels in Lower Fields below given altitude (A) and within given distance of a major drainage (B) in 1990 (?) and in 2000 (+).

CONCLUSIONS

Interactions between humans and their environment change over time. Sometimes the most evident driver for change is environmental—a drought that forces migration, a cooling that shortens the growing season—and sometimes the driver seems to be exclusively cultural—famine induced by war, deforestation facilitated by tractor and chainsaw. Ultimately, however, the relationship between humans and their natural resources emerges from the interface of environmental and cultural processes, and the result is a land mosaic of modified and undisturbed ecosystems. In the Lower Khabour Basin this mosaic changed significantly over the course of the 20th century, and the rate of change in the last decade is particularly striking. In an environment where agricultural production in impossible without irrigation, changes in the technologies of water diversion and extraction have led to a changed distribution of human settlement in the landscape. In the past farms were clustered together along the floodplain;

today irrigated fields and the diesel-powered hydraulic pumps that feed them are scattered across the steppe. In the future, government-sponsored canal networks may lead to a new pattern of clustering, as already observed in neighboring watersheds of Turkey and Iraq, with farms packed into grids defined by engineering and politics rather than riparian or groundwater hydrology.

The physical impacts of such changes are not entirely understood. Groundwater extraction has lowered the water table in the Khabour, and it is believed that this extraction is the primary reason that the Lower Khabour River has run dry in every summer since 1999. Loss of the river has nearly ended summer floodplain agriculture on the southern stretch of the floodplain, and the disruption of the riparian ecosystem has been enormous. In other parts of Syria extraction of groundwater has led to salt water intrusion, reduction of irrigation water quality, and secondary salinization of agricultural soils (Hoogeveen et al., 1999). The transfer of agriculture out of the sheltered floodplain to the windy steppe, and the shift from clustered irrigation patches to dispersed fields, may further encourage salinization on account of increased evaporation rates. Yields may suffer as well, due to water stress in the open steppe and rapid degradation of soils that have never before been used for intensive agriculture.

The physical impacts of canal irrigation are quite different. Hydrologically, reservoir and canal networks are prone to large evaporative losses, and the quality of return waters from these systems can be quite low. Leakage is also a major concern in developing a water-efficient canal system, and canal maintenance has proved to be a problem for extant diversion schemes in Syria. The effect of major canal networks on microclimate is a subject of considerable interest. It is believed that the tight packing of fields and broad extent of irrigation in places like the Harran Plain may influence humidity, temperature, and perhaps even precipitation within the irrigated area and downwind of it.

The social impact of water withdrawal technologies is also significant. Deep well extraction systems have empowered farmers with access to high quality groundwater and good soils in the steppe. Communities that depend on surface water for irrigation have suffered, as both the reliability and quality of water in the river have declined. There are accusations that this shift in water resources has been accelerated by political interests (AINA, 2000). The establishment of dams, diversions, and canal networks places control of water and land more firmly in the grip of the government; high value agricultural land can be created virtually independently of natural hydrology, and settlement patterns on the steppe can be determined by those who draw the diversion plans. Indeed, there is a long history of using canal projects to settle populations and to accrue economic benefit (Reisner, 1993; Scott, 1999).

Through remote sensing it is possible to monitor spatial changes in the landscape as they occur. It is essential that we be able to quantify the spatial distribution and patterns of landuse observed in remotely sensed images in order to better understand the dynamics of change within the landscape and, ultimately, to trace their environmental and social correlations and consequences.

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