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Demand effect of land use on water ─ A case study of North China Plain

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Abstract
Land is one of the most important assets of sovereign nations and humans derive virtually all essentials of life from land. In spite of this, land use does not always produce desired effects or could even threaten the life it is supposed to support. This calls for time-to-time land use analysis to ensure that ecosystem services are sustained, food chain stopgaps are eliminated, the environment is preserved and life is sustainable. Water is a small but critical component of terrestrial land surfaces. This precious but fragile resource is fast depleted in especially the more populated (semi)-arid regions across the globe. Thus, this study analysis land use change in relation to water resources availability in the semi-arid North China region. The study analyzes two Landsat satellite scenes (September 1979 and August 2009) in ENVI (Environment for Visualizing Images) and ArcMap environments and only results with less than 10% errors accepted. The analysis shows that the area of land under water in 1979(2009) is 1.8% (0.6%); suggesting some 63.8% loss of surface water resources in the region. For 1979–2009, there is respectively 54.3% and 71.5% loss in the area of land under forest and wood-grass. Also, the gain in settlement, farmland and others is respectively 64.8%, 56.5% and 53.9%. Although water accounts for only 1.9% of the average land use change in the study area, it is an irreplaceable element of life and the ecosystem. It is therefore important that future land use activities take measures (such as revegetation of headwater regions) to ensure that the limited and fragile water resources in the study area are sufficiently protected.

Keywords: North China, Landsat scene, Land use, Surface water, Sustainable management

Introduction

As one of the most important resources, nations derive virtually all essentials of life from land. Land cover is the physical characteristics of the earth's surface, including vegetation, soil and water (*Ramachandra & Kumar* 2004) [13]. In this context, land use is defined as the allocation of portions of the land to the needs of society or environment (*Zhang et al.* 2010) [20]. Land use factors are dependent on the level of socio-economic development. Although the conversion of extensive forests into agricultural lands started over a century ago (*Junkermann et al.* 2009) [6], rapid socio-economic developments accelerated land use change especially in the last half of the 21st century (*Prince et al.* 2009) [12]. However, land use does not always produce desired effects. This is evident in the increasing trend in e.g., land degradation and water resources depletion especially in populated and intensively cultivated (semi)-arid regions (*Gao & Liu* 2010) [3].

The monitoring and mitigation of the negative consequences of land use while maintaining optimum production remain a daunting challenge to researchers, planners and decision-makers. This is because understanding the myriad interrelated complexities of land use and environmental feedback requires processing huge amounts of data (van *Niekerk* 2010) [17]. Remote Sensing (RS), Geographic Information System (GIS) and Global Positioning System (GPS) are promising data processing techniques with large data capture and handling capacities. These geo-spatial techniques could be used either separately or in combination with distributed land-state models to determine the impacts of human activity on changes in land use, climate conditions and hydrological processes (*Rodell et al.* 2004 [14]; *Zhang et al.* 2010) [20].

RS is a sensor-based multi-spectral system designed to repeatedly collect data over large spatial scales. The ENVI (Environment for Visualizing Images) scientific software processes large-scale, multi-band images. Then the GIS flexible platform stores, analyzes and displays multi-resolution digital data. Such geo-spatial techniques are not only efficient in terms of cost, time and labor (*Long et al.* 2008) [9], but also capture data with almost unlimited scope of application. Satellite data are widely used in analyzing land use (*Zhang et al.* 2010) [20], evapotranspiration and net primary productivity (*Prince et al.* 2009) [12], land integrity (*Gao & Liu* 2008 [2], 2010) [3], surface temperature and climate change (*Zhang et al.* 2005) [21], water resources (*Moiwo et al.* 2010) [11] and environmental degradation (*Li et al.* 2008) [7].

Change detection analysis broadens existing knowledge on the implications of land use for sustainable environment and livelihood. Digital change analysis and detection is among the several techniques for analyzing and detecting physiological changes in landscapes (*Ramachandra & Kumar* 2004) [13]. It includes vector analysis (*Bayarjargal et al.* 2006), differencing (*Desclee et al.* 2006) [1], rationing (*Zhao et al.* 2004) [22] and regressing (*Gao & Liu* 2010) [3] of RS images or their various combinations (*Ramachandra & Kumar* 2004) [13]. Post-classification analysis is by far the most wildly used digital change detection technique (*Gao & Liu* 2008) [21]. This is because it reveals not only the nature, but also the extent of change in the landscape (*Zhang et al.* 2010) [20]. Information derived from post-classification analysis is linked to the factors of land use change for applications in land reform, resource exploitation and environmental management (*Li et al.* 2008 [7]; *Gao & Liu* 2010) [3].

China is witnessing aggressive land use dynamics since the 1949 Maoist Revolution (*Liu et al.* 2010). The staggering population, the surging socio-economic growth and the intensive resource exploitation are key drivers of land use change in China (*Moiwo et al.* 2010) [11]. Drastic land use change in particularly the semi-arid North China could trigger water-scarcity crisis in the region. It is noted that clearing mountain forests for farmlands triggers land degradation, flooding in times of rainstorms and drought in times of dry spells (*Zhang et al.* 2010) [20]. Deforestation also suppresses precipitation (*Junkermann et al.* 2009) [6] and vegetation growth that in turn accelerate land degradation (*Gao & Liu* 2008) [10].

The intricate inter-connectedness of land use and land-state processes necessitates a comprehensive land use analysis for sustainable management of resources. Thus this study analyzes land use change in the fast urbanizing/industrializing and agricultural active North China region. The study examines the driving factors of land use change and advances reform strategies for sustainable management. This package could equip resources managers to develop informed plans and take data-driven decisions in implementing policies regarding land/water resources use and ecological sustainability in the region.

Materials and method

Study area

The North China study area lies northeast of Baiyangdian Lake between latitudes 38.10–39.62 °N and longitudes 114.15–115.88 °E (Figure 1). The area, which includes Baoding City and 19 contiguous counties (Figure 1), has an average area of 23 826 km^2. The activities in Baoding (the largest settlement in the area) significantly influence the use of land/water resources in the region.

The semi-arid monsoon climate influences the pattern and dynamics of precipitation in the region (*Moiwo et al.* 2010) [11]. About 75% of the ≈450 mm annual precipitation falls in June through August (*Tian et al.* 2009) [15]. Evapotranspiration, especially in cultivated lands, is over two times (>900 mm) the annual precipitation (*Zhao et al.* 2010) [23]; affecting water availability for industrial, agricultural and domestic use (*Zhang et al.* 2010) [20]. There are four distinct seasons, with the highest temperature (32 °C) in summer and the lowest (-28 °C) in winter (*Zhao et al.* 2010) [23]. Crop growth in the study area is most favorable in the spring and summer seasons (*Yang et al.* 2010) [19].

Winter wheat and greenhouse farming are fast-increasing agronomic practices in North China (*Yang et al.* 2010) [19]. Natural land cover, which is mainly forest in the mountains and wood-grass in the floodplains (*Liu et al.* 2010) [8], has shrunk drastically following the 1949 revolution and its subsequent land reforms. Since then, government polices are more focused on food self-sufficiency in the country (*Tian et al.* 2009 [15]; *Zhao et al.* 2010) [23].

While the northwestern half of the study area is mountainous (with surface elevations over 2000 m), the southeastern alluvial floodplains (with surface elevations below 50 m) are generally flat, densely populated and intensively cultivated. The region is drained into the South China Sea via a network of rivers/lakes (Figure 1). Intensive water resources exploitation (over the decades of rapid socio-economic growth) has reduced once the perennial into ephemeral or waterless rivers/lakes (*Moiwo et al.* 2010) [11]. Groundwater depression cones due to over-pumping are reported in the floodplain region (*Yang et al.* 2002 [18]; *Hu et al.* 2010) [5]. The mounting stress on the available land/water resources cause not only water shortage, but also threatens crop production and the fragile ecosystem.

Data collection

Long-term changes in land use are detectable by comparing co-registered multi-spectral images (*Geymen & Baz* 2008) [4]. Information on changes in habitat fragmentation, deforestation, urbanization, etc. is vital for planning and policy decisions that affect grassroots communities in terms of land use and sustainable livelihood (*Gao & Liu* 2010 [3]; *Moiwo et al.* 2010) [11].

RS Landsat images are widely used in the study of hydrogeological and land-state processes such as land use change, climate change and mineral exploration including water (*van Niekerk* 2010 [17]; *Yang et al.* 2010) [19]. In this study, a pair of Landsat images is used to evaluate land use change in the niche northeast of Baiyangdian Lake. Landsat-MSS (4-band, 60-m spectral resolution image) scene for 6 September 1979 and Landsat-TM (7-band, 30-m spectral resolution image) scene for 12 August 2009 are ordered at http://edcsns17.cr.usgs.gov/EarthExplorer/ for the study. The Landsat scenes represent a timeframe for sufficient land use change detection in the region. Ground-truth data constitute field survey observations in the study area.

Image data processing

The acquired Landsat images are radiometrically and geometrically corrected (in terms of projection, orientation and pixel size) in the ENVI (Environment for Visualizing Images) environment. For instance, the multi-spectra zero-cloud effect images are geometrically co-referenced and projected into WGS-1984 UTM (Universal Transverse Mercator) Zone-50N coordinate system for the study area. For the Landsat-TM scene, thermal infrared band six (which has a different spatial resolution from the other bands) is excluded from the analysis. Because the spatial coverage of Landsat-MSS is different from that of Landsat-TM scene, only the common region of intersection (which is half mountain and half floodplain; see Figure 1) is processed in the analysis.

Also, as the focus here is on water availability as influenced by land use change, only open-water, settlement, forest, wood-grass, farmland and others are considered. Wetlands with sufficient standing water, forest, wood-grass, crops are respectively put under the dominant land use type. Otherwise, degraded lands and all other forms of land surfaces are lumped together as others. Land use not only changes the micro-climatic conditions, but also suppresses precipitation, and induces vegetation loss and soil degradation (*Junkermann et al.* 2009 [6]; *Tian et al.* 2009) [15]. As explained in the next sections, ENVI and ArcGIS platforms are used to analyze the Landsat scenes for land use change in the study area.

ISO data classification

The Iterative Self-Organizing Data Analysis Technique Algorithm (ISODATA; *Tou & Gonzalez* (1974) [16] can classify large datasets into clusters of homogeneous properties. ISODATA is an unsupervised classification method that combines iterative and heuristic procedures in computing clusters (*Melesse & Jordan* 2002) [10]. It repeats image clustering until classes of pre-defined criteria are met (*van Niekerk* 2010) [17]. The algorithm starts by randomly selecting cluster center points within an input data space. Each pixel is then grouped into a candidate cluster by minimizing a distance function between a pixel and its cluster center. After each iteration, cluster means are updated by further splitting/merging; depending on the size/spread of data points within the cluster (*van Niekerk* 2010) [17]. ISODATA computes a spectral distance based on the Euclidean distance equation (*Melesse & Jordan* 2002) [10] as follows:

$$\theta_{xy(c)} = \sqrt{\sum_{i=1}^{n}\left(\mu_{ci} - \lambda_{xy(i)}\right)^2} \quad (1)$$

where n is number of bands; i is ith band number; c is class; $\lambda_{xy(i)}$ is data file value of pixel x, y in band i; u_{ci} is mean data file value (digital numbers) of band i in class c sample; and $\theta_{xy(c)}$ is spectral distance from pixel x, y to class c mean.

Here, preliminary classifications of Landsat images are set to a maximum of five spectral classes. The output five class images are then recoded into the land use classes defined above. During the recoding, the identity of a land use in a spectral cluster is determined by visual interpretations of original satellite images and field-survey data. Next, a post-processing confusion matrix is conducted to analyze omission/commission errors in the recoded classes. Successful post-processing results is accepted as satisfactory when the confusion matrix <10%. The accepted images are then overlaid and differenced in ArcGIS for land use change.

Land use change identification

Land use change is determined using the grid-based analytical method presented by *Long et al.* (2008) [9]. To achieve this, the Landsat-MSS grid resolution is matched with that of Landsat-TM data. Next, land use change for corresponding pairs of grid-cells is computed as change matrix (*Long et al*. 2008) [9]:

$$LC_i = \left(\frac{R_i - C_i}{C_i}\right) \times 100 \quad (2)$$

where LC_i is percent change in land use relative to earlier land use in row i; R_i is row total of grid-cells in land use class i; and C_i is column total of grid-cells in land use class i.

Next, the percent loss/gain in a land use class is calculated as:

$$PL_{i,j} = \left(\frac{P_{j,i} - P_{i,j}}{R_i - C_i}\right) \times 100; \quad PG_{i,j} = \left(\frac{P_{i,j} - P_{j,i}}{R_i - C_i}\right) \times 100; \quad i \neq j \quad (3)$$

where $PL_{i,j}$ is percent loss in row i due to conversion into class j; $PG_{i,j}$ is percent gain in row i due to conversion into class j; and $P_{i,j}$ and $P_{j,i}$ are discrete entries into the change matrix in Eq. (2). The results of the analysis are presented and discussed in the next sections.

Results and analyses

Figure 2 plots the unprocessed images of the two Landsat scenes used in this study. On the satellite scenes are delineated selected settlement and water surfaces with direct visible changes during 1979–2009. Some of the surfaces are further expanded for greater visualization in the bottom plates of Figure 2. The plots show clear dwindling surfaces under water and forest against expanding surfaces under settlement and farmland in the study area. This suggests that land use change negatively affects available water resources in the study area.

For deeper insight into the dynamics of surface water resources in the study area, the Landsat scenes are classified into limited land use types. To also deepen existing knowledge on the magnitude of land use change in the region, only the selected surfaces in Figure 2 (bottom plate) are displayed (in Figure 3) for the classified image scenes. The changes in land surfaces under water, forest, farmland and settlement during 1979–2009 are obvious in the classified plates in Figure 3.

In the water-dominant plate for 1979 (Figure 3***a1***), 45.9% of the land area is forest, 26.0% is farmland, 20.0% is water, 5.2% is wood-grass, 2.5% is settlement and 0.4% is others. Then by 2009 (Figure 3***a2***), the area of land under wood-grass, forest and water drops respectively by 92.5%, 77.0% and 45.4%. That under settlement, farmland and others increases respectively by 199.0%, 170.7% and 6.0%. Similarly in the settlement-dominate plate for 1979 (Figure 3***b1***), 64.9% of the land area is farmland, 18.4% is settlement, 13.2% is wood-grass, 3.0% is water, 0.3% is others and 0.2% is forest. Then by 2009 (Figure 3***b2***), the area of land under wood-grass, water, farmland and forest drops respectively by 99.2%, 83.5%, 28.0% and 24.5%. Also, the land area under others and settlement increases respectively by 2451.7% and 140.6% (see Table 1 for further details).

Farmland, forest, grass, settlement, water and others account respectively for 43.8%, 29.5%, 17.4%, 7.4%, 1.8% and 0.1% of the study area in 1979. The by 2009, the area of land under water drops by 63.8%. Land areas under grass and forest drop respectively by 71.5% and 54.3% as those under settlement, farmland and others concurrently increase by 64.8%, 56.5% and 53.9%. It is then evident that the conversion of natural land cover system into various other forms of land use negatively affects the availability of water in the study area (*Tian et al.* 2009) [15]. As a key element of watersheds, vegetation maintains water quality/flow by reducing runoff during rainstorms and supporting base-flow during dry spells. Land use change could therefore be the major driver of the growing water shortage in the region.

Discussions

Land use is linked to weather/climate in complex ways and is a critical input for modeling water availability and ecosystem health. Analysis of land use change strengthens understanding of the interactive feedbacks of landscape heterogeneity and anthropogenic activity and how these relate to climate change, ecosystem health and sustainable livelihood. Figuring out the links among past, current and future land use change and the drivers of it is critical for the sustainability of the human world.

This study analyzes land use change in relation to water availability for 1979–2009 in North China — an actively developing and heavily populated semi-arid region. The study shows that significant amounts of the natural land cover system are converted into other forms of land use, negatively affecting water availability in the region. With respectively 71.5% and 54.3% reductions in grass and forest covers along with 64.8%, 56.5% and 53.9% increases in settlement, farmland and others, there is 63.8% reduction in the surfaces under water in the region. Such huge loss of surfaces under water could trigger wider negative implications for the micro-climate, eco-environment and human livelihood.

For 1979–2009, farmland accounts for 41.8% of the total land use change in the study area. This is followed by forest (27.0%), grass (21.0%), settlement (8.1%), water (1.9%) and others (0.1%). It is then deductive from the analysis that the quest for food self-sufficiency for the 1.3 billion people forces expansions of farmlands, which in turn accelerates the rate of deforestation and water shortage in the region. Farming activities are reported to suppress precipitation by changing atmospheric aerosol composition. Winter wheat cultivation is further noted to result in far higher evaporation than under natural vegetation (*Junkermann et al.* 2009) [6].

Natural vegetation is a crucial component of the ecosystem and food chain. The negative ecological consequences for over-disturbances of natural vegetation could create stopgaps in the food chain. For instance, forests maintain water quality, moderate peak-flows, reduce runoff, prevent flooding, support base-flows and provide habitat (food source and breeding ground) for arboreal/terrestrial species. The conversion of natural vegetation into other land use forms could destroy fragile wetlands with other vital ecological niches, which in turn speeds up environmental degradation and climate change. Thus, land use trend (especially that of deforestation) is a useful indicator for land degradation, water availability, food security and human sustainability (*Gao & Liu* 2010) [3]. This indicator factor could be used for policy plans for the sustainable management and land cover systems including surface water.

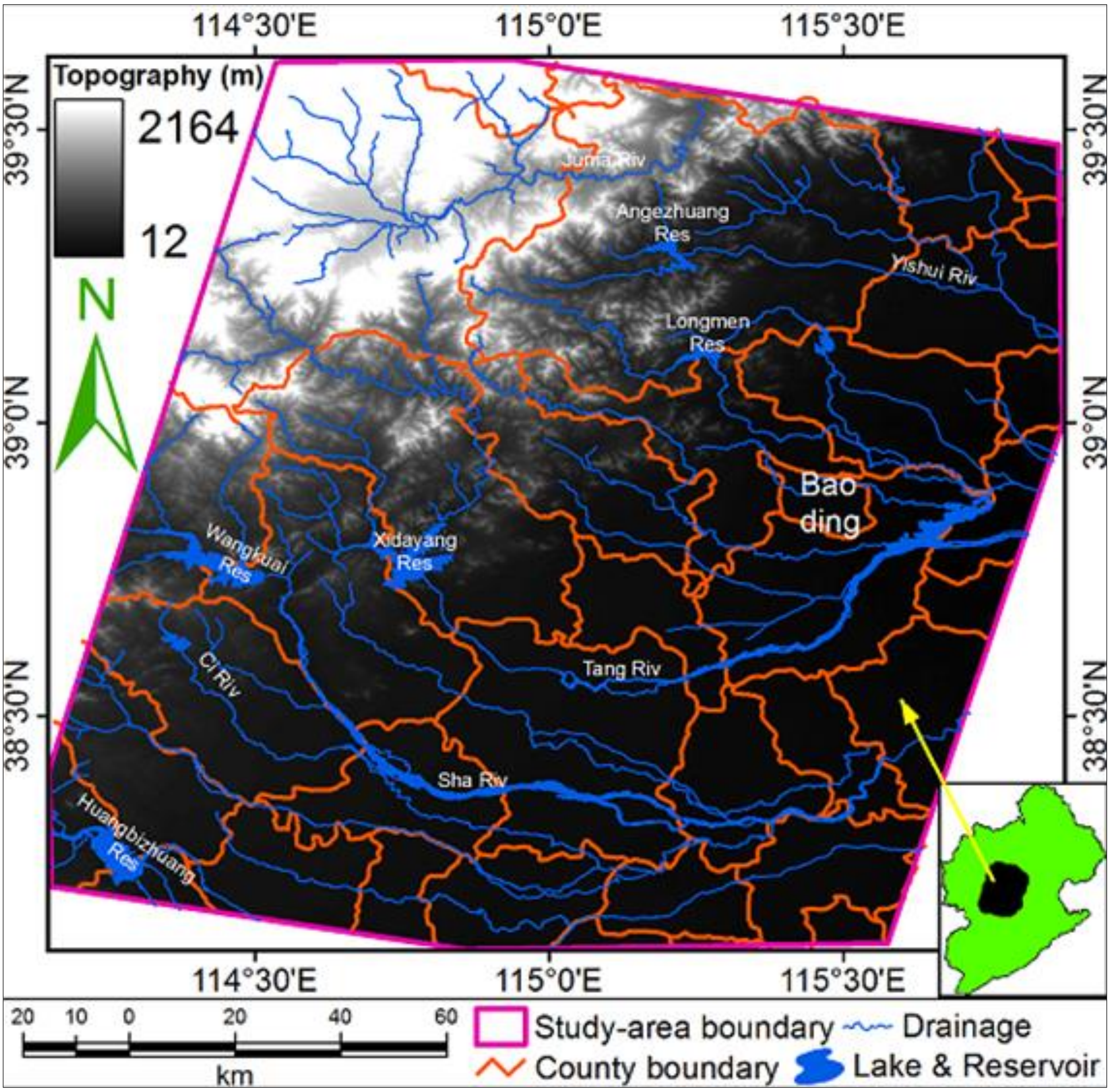

Fig 1: A map showing the location of the study area in the Hai River Basin (bottom right-corner inset) along with the counties, drainage system (rivers/lakes), Baoding City and the background topography.

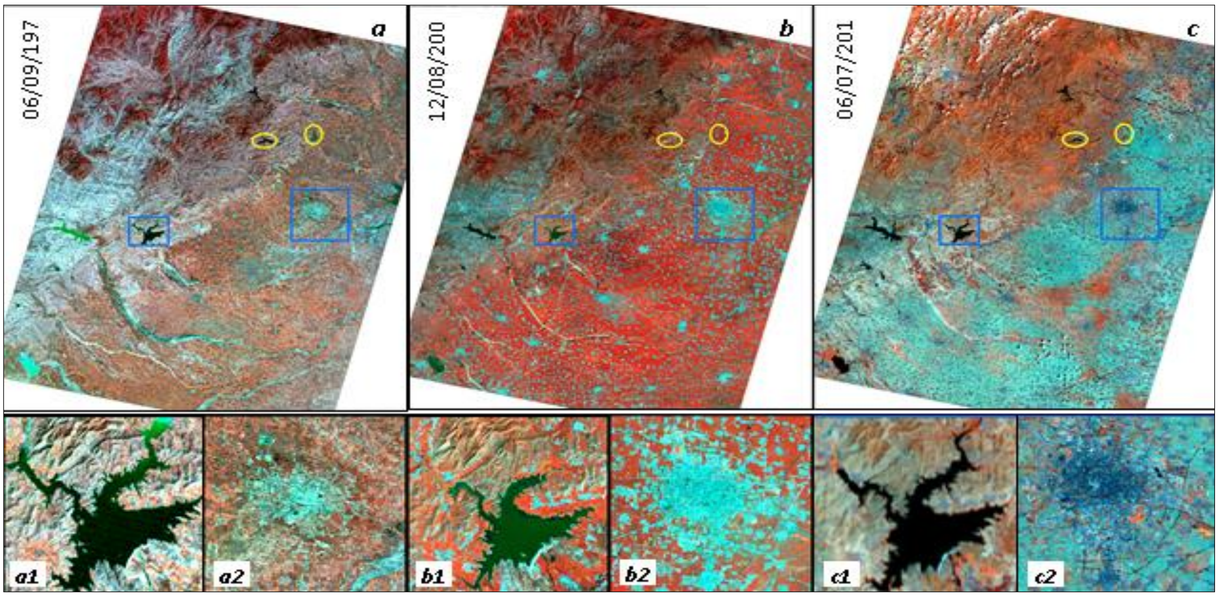

Fig 2: Plots delineating visually detectable land use changes in raw satellite Landsat-MSS/TM+ scenes for 06/09/1979 (plate ***a***), 12/08/2009 (plate ***b***) and 06/07/2013 (plate ***c***) in the study area. Note that scenes ***a***, ***b*** & ***c*** are co-referenced along with the rectangular and oval delineations on the plates. The bottom plates are expansions of the rectangular insets illustrating further the land use change during 1979–2013 in terms of water (***a1***, ***b1*** & ***c1***) and settlement (***a2***, ***b2*** & ***c2***) in the study area.

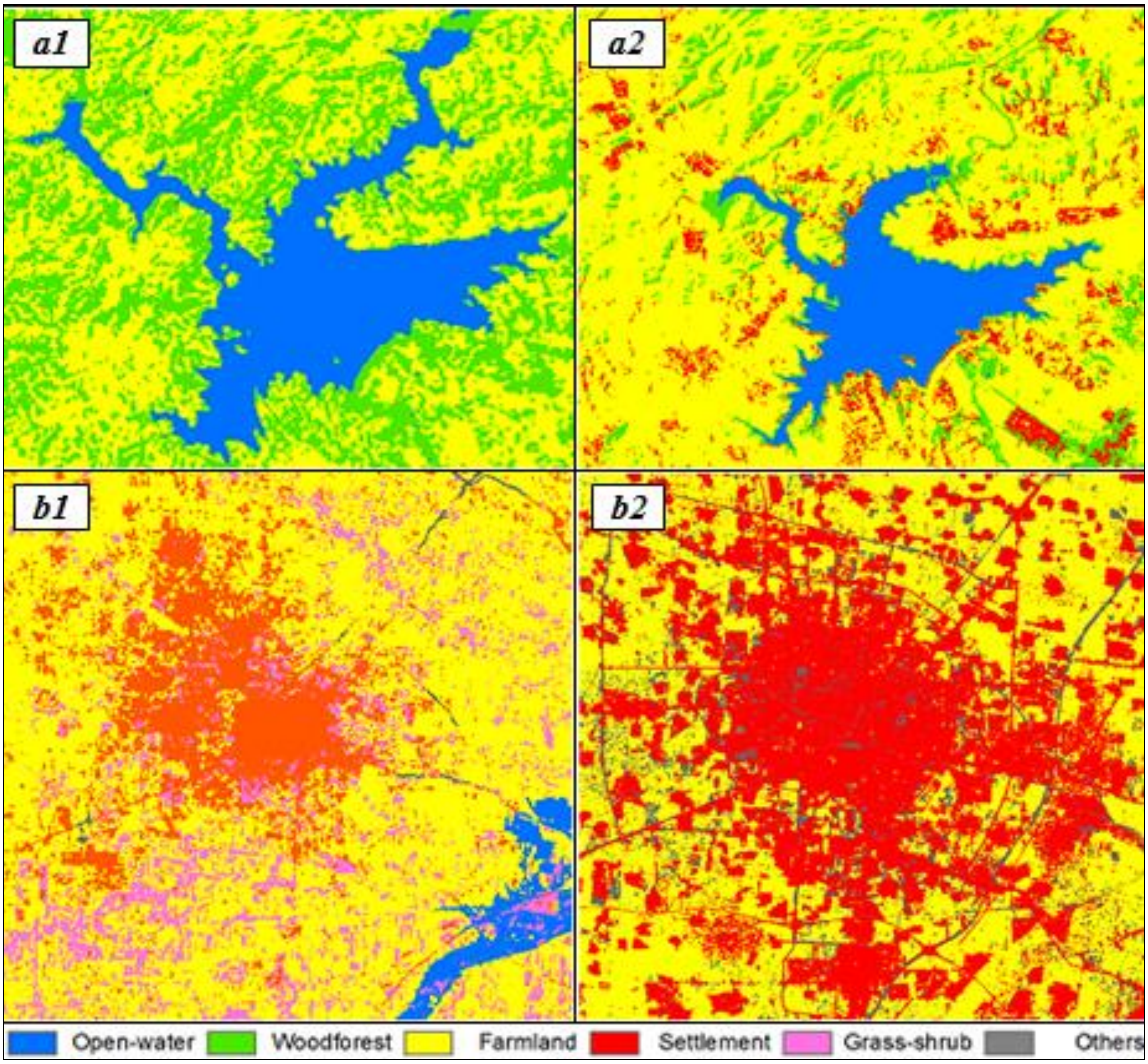

Fig 3: Representative plot of the classified Landsat image scenes illustrating land use change in the selected land surfaces in Figure 2 (bottom plate) during 1979–2009 in the study area. Note that plots **A1** & **A2** are mainly for open-water surfaces and **B1** & **B2** for surfaces with settlement.

Table 1: Detailed characteristics of land use change in the North China study area for the period 1979–2009

Land use	1979		2009		Gain/Loss	
	Area (km^2)	Percent (%)	Area (km^2)	Percent (%)	Area (km^2)	Percent (%)
Water-dominant plate (Figures 3***a1*** & ***a2***)						
Water	32.0	20.0	17.5	10.9	-14.5	-45.4
Forest	73.3	45.9	16.8	10.5	-56.5	-77.0
Grass	8.4	5.2	0.6	0.4	-7.7	-92.5
Farm	41.5	26.0	112.3	70.3	70.8	170.7
Settlement	3.9	2.5	11.8	7.4	7.8	199.0
Others	0.7	0.4	0.8	0.5	0.0	6.0
Total	159.8	100.0	159.8	100.0	0.0	
Settlement-dominant plate (Figures 3***b1*** & ***b2***)						
Water	15.0	3.0	2.5	0.5	-12.5	-83.5
Forest	0.8	0.2	0.6	0.1	-0.2	-24.5
Grass	65.6	13.2	0.5	0.1	-65.1	-99.2
Farm	322.6	64.9	232.4	46.7	-90.3	-28.0
Settlement	91.6	18.4	220.3	44.3	128.7	140.6
Others	1.6	0.3	41.0	8.2	39.4	2451.7
Total	497.3	100.0	497.3	100.0	0.0	
The entire North China study area (Figures 1***a*** & ***b***)						
Water	427.7	1.8	154.8	0.6	-272.9	-63.8
Forest	7027.9	29.5	3211.7	13.5	-3816.1	-54.3
Grass	4148.7	17.4	1182.4	5.0	-2966.3	-71.5
Farm	10441.9	43.8	16345.0	68.6	5903.2	56.5
Settlement	1762.9	7.4	2906.1	12.2	1143.1	64.8
Others	16.7	0.1	25.7	0.1	9.0	53.9
Total	23825.7	100.0	23825.7	100.0	0.0	

Conclusions

Sustainable management of land/water resources requires a sound insight into the distributions and changes of these resources in space and time. This study analyzes the changes in land areas under water and other land use types in the North China study area (half mountain and half plain) for 1979–2009. Two Landsat scenes (for September 1979 and August 2009) are analyzed in ENVI and ArcMap environments for land use dynamics in the region.

For individual land use types, the highest change (63.8%) is for land surfaces under water. The loss of surfaces under water occurs along with loss of surfaces under grass (71.5%) and forest (54.3%). Concurrently, there is 64.8%, 56.5% and 53.9% gain respectively in settlement, farmland and other land use types in the region. Other uses, water, settlement, grass, forest and farmland respectively account for 0.1% ((0.1%), 1.8% (0.6%), 7.4% (12.2%), 17.4% (5.0%), 29.5% (13.5%) and 43.8% (68.6%) of the study in 1997(2009); representing 53.9% gain, 63.8% loss, 64.8% gain, 71.5% loss, 54.3% loss and 55.6% gain in land areas under the respective land use types. For the entire study area, however, these land use types respectively account for 0.1%, 1.9%, 8.1%, 21.0%, 27.0% and 41.8% of the average change in land use. Despite its vitality or even because of it, water (also the second smallest land use type in the region) is fast disappearing. This shows how fragile this life-sustaining element is and thus stresses the urgency for efficient preservation measures to ensure broader sustainability. Although concern is increasing for possible future crisis, the effects of land use change are generally reversible through more sustainable measures like afforestation and/or reforestation.

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