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Mapping wetland cover in the greater Himalayan region: a hybrid method combining multispectral and ecological characteristics

Zhuoqing Li · Jianchu Xu · Rajendra L. Shilpakar · Xing Ma

Abstract In the greater Himalayan region, wetland ecosystems such as lakes, marshes, and peat lands play an important role in regulating the flow of major rivers. These ecosystems are often overlooked and not well represented on land-use planning and conservation maps. Wetland complexes are partly ephemeral and difficult to map accurately either with digital image processing or visual interpretation. This study developed a hybrid method of extracting spatial patterns of wetland areas which combines month-on-month multispectral classifications of Moderate Resolution Imaging Spectroradiometer data with a sample wetland extraction method based on knowledge of the spectral characteristics of satellite data and wetland ecological systems. The results were compared with the best available sources for lakes and wetlands on global and national scales. It was demonstrated that the method could extract wetlands automatically to a reasonable degree of accuracy and, therefore, reduce the need for extensive ground knowledge. The model was transferred by adjusting parameters through application of high-resolution satellite data (Landsat) in some sub-basin areas. These findings are cognizant with field interviews conducted by wetland experts. The hybrid method and high-altitude wetlands maps will provide decision makers with valuable information about wetland distribution and change in response to global warming and human activities.

Keywords Wetland extraction · Hybrid model · High-altitude wetlands/lakes · Greater Himalayan region

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Introduction

The ecological functions and services of the greater Himalayan wetlands in regulating river flows and maintaining grassland productivity are essential for the sustainable development of more than 10 countries in Asia. These 10 countries have at least 140 million people living in high-altitude areas and 1.3 billion people who live downstream of 10 river basins (Ramsar 2002; Xu et al. 2009). Geographically the greater Himalayas cover the Qinghai-Tibetan Plateau as well as the Pamir Plateau and other mountain ranges.

The Himalayan wetlands are the sources of many rivers: the Amu Darya, Indus, Ganges, Brahmaputra, Irrawaddy, Salween, Mekong, Yangtze, Yellow, and Tarim. Among the most powerful forces that impact the wetlands and their ecosystem services are increasing human activities and climate change (Wang et al. 2006; Li et al. 2008). Population growth, urbanization, conversion of land to agricultural and pasture land, recreation, and tourism development threaten the wetlands. The impacts of climate change are also superimposed on a variety of other environmental and social stresses. High-altitude wetlands are sensitive

indicators to global climate change; the impacts of their hydrological processes and the downstream chain effects are more severe than elsewhere.

The Himalayan wetlands are important ecosystems as they provide temporary water storage, regulate flows, and reduce the risks of floods. They are also important for their rich biodiversity, cultural and spiritual services (Ramsar 2002). The wetlands on the Tibetan Plateau are one of the hotspots for biodiversity, harboring many endemic and endangered species, including Grus nigricollis, a plateau crane (Xiang et al. 2009). A combination of factors from climate change and human activities has led to the degradation of many wetland ecosystems in the greater Himalayas (An et al. 2007). Loss of vegetation and degradation of wetlands increases exposure of the soil surface which in turn increases emission of methane (CH_4) into the atmosphere (Chen et al. 2008), thus contributing to global climate change.

High-altitude wetlands are dynamic because they are transitional features between land, grassland, and water habitats. While temperature permits, over time most wetlands gradually fill in: many wetlands were originally lakes or other bodies of water. Tons of plants, animals, and insects grow and die in them each year. Gradually over time, the decaying material from these organisms accumulates in small lakes and the lake becomes wetlands. The process continues with the wetlands expanding into wetland complexes with deep deposits of peat and substantial water-holding capacity. Among the wetlands, peatlands have large stores of carbon, particularly the wetlands at the headwaters of the Mekong, Yangtze, and Yellow rivers (Wu et al. 2003).

Himalayan wetlands support large populations of migratory birds which come to reproduce (Zhou and Chen 2006). The biodiversity of a wetland is maintained by its own particular conditions. In addition to their national significance their regional distribution is of particular interest in terms of assessing current and future water resources, studying climate change, carrying out hydrological modeling; and for large-scale studies of land-use// land-cover change, ecosystem services, and food security (Xu et al. 2009).

However, no comprehensive inventory of the wetlands has been made and monitoring is hampered by poor accessibility and rugged topography. Knowledge about the distribution of lakes and wetlands is of great interest, therefore, to many scientists and policy makers. To date, there are very few detailed regional data sets on location and other features of high-altitude wetlands. The existing global spatial data (Lehner and Doll 2004) are too coarse and do not represent the Himalayan region well, whereas existing national and local datasets do not cover the entire region (Cai et al. 2007). A review of Ramsar's Himalayan

Wetlands Conservation Initiative recommended a regional database for inventory, monitoring, and use of high-altitude wetlands.

Remote sensing (RS) has proven to be a powerful and cost-effective tool for collecting spatial data in areas difficult to reach. The use of RS techniques to map wetlands is now readily accepted, although there are still many methodological problems (e.g., accuracy assessment), and hydrological data, and a better understanding of the dynamics of change (Ozesmi and Bauer 2002; Smith 1997). The recent availability of medium to low resolution satellite data from instruments such as moderate resolution imaging spectroradiometer (MODIS) facilitates regional scale land-cover mapping. The MODIS sensor on board the Terra and Aqua platforms with 36 spectral bands, extending from the visible to thermal infrared, at resolutions of 250, 500, and 1,000 m and capturing two images per day is suitable for rapid wetland assessment and monitoring in regions like the Himalayas. Recently, studies have demonstrated the usefulness of MODIS data for assessing land cover (Friedl et al. 2002) and phenological patterns of vegetation (Zhang et al. 2004) on regional scales. Pu et al. (2007) successfully used MODIS data to map the snow cover over the Tibetan Plateau.

This study is part of the EU-Asia Pro Eco Programme for the Himalayan Initiative through application of the Asian Wetland Inventory approach and stakeholder-led catchment management in the Himalayan region. As suggested by the regional member countries participating in the Himalayan Initiative (ICIMOD 2003), wetland cover, including lakes and river systems situated above 3,000 m, are considered as Himalayan wetlands. Defined as the 'Asian water tower', the area provides approximately 8.6×10^6 m^3 of water annually (Xu 2007; Xu et al. 2009). At high altitudes, water is often stored as glaciers, ice, and snow as well as lakes, rivers, and wetlands. This study focused on mapping primary wetland types, such as lakes, marshes, and rivers, using remote-sensing data on the Himalayas based on the modified Ramsar classification of wetlands. Large rivers are included as wetlands for assuming that only a river with adjacent wetlands (floodplains) is wide enough to appear as a polygon on the coarse-scale source maps.

The authors also looked at the biophysical distribution patterns of Himalayan wetlands by applying 3S [RS, geographical information system (GIS), and geographical positioning system (GPS)] technology on both local and regional scales. The aim of this study was to advance the development of a rapid, low-cost wetland mapping protocol which can be used to evaluate the response of high-altitude wetlands to changes in the climate and environment of the greater Himalayan region. Credible scientific information has been provided in spatial format for

decision makers and conservation managers as a means of facilitating the wise use and conservation of high-altitude wetlands locally and regionally in the greater Himalayan region.

Materials and methods

Study area

The greater Himalayan region extends from 3,000 masl (meter above sea level) and includes the whole of the Tibetan Plateau, most parts of the Pamir Plateau, as well as the Hindu-Kush Himalayan mountain ranges (Fig. 1). It is the world's largest and topographically most complex high plateau with coverage of around 3.8 million km^2 lying between latitudes N24°53′–45°47′ and longitudes E64°46′–105°9′. The Himalayas are characterized by a high density of glaciers, lakes, and wetlands as well as large areas of permafrost coverage. Average minimum temperatures range from −5.64 to −12.34 °C in January; average maximum temperature is about 16.05 °C in July; and an annual average is <2 °C.

As the world's 'Third Pole', the Himalayan region is one of the most sensitive areas to global climate change. The Tibetan Plateau is an important factor in the atmospheric circulation processes affecting the plains of northern China and the development and evolution of the so-called 'Asian Monsoon'. Distinct variations in rainfall occur along elevational gradients as well as between the southern rim of the Himalayas and the rain-shadow areas of the Tibetan Plateau. On the meso-scale, climatic impacts are influenced by local topographic characteristics (Chalise and Khanal 2001). Climate also controls glacial mass balance and river flows and a substantial amount of annual precipitation falls as snow, particularly above 3,000 m. The greater Himalayan ranges have 116,180 km^2 of glacial ice, the largest area outside the polar region (Owen et al. 2002; Li et al. 2008).

Throughout the Himalayas, water melts from permanent snow and ice and seasonal snow packs and is stored in wetlands and lakes at high altitudes. The contribution of snow and glacial melt to the major rivers in the region ranges from <5 to more than 45 % of the annual average flow (Xu et al. 2009). Melting snow and ice contribute about 70 % of the summer flow in the main Ganges, Indus, Tarim, and Kabul rivers during the shoulder seasons before and after precipitation from the summer monsoon (Singh and Bengtsson 2004; Barnett et al. 2005). The contribution of glacial melt to flows in the inner Asian rivers is even greater than this (Xu et al. 2004; Chen et al. 2006). The Indus river irrigation system in Pakistan depends on snow and glacial melt from the eastern Hindu Kush, Karakoram, and western Himalayas for about 50 % of total runoff (Winiger et al. 2005). In western China, about 12 % of the total discharge is runoff from glacial melt, and it provides

Fig. 1 Location of the greater Himalayan region
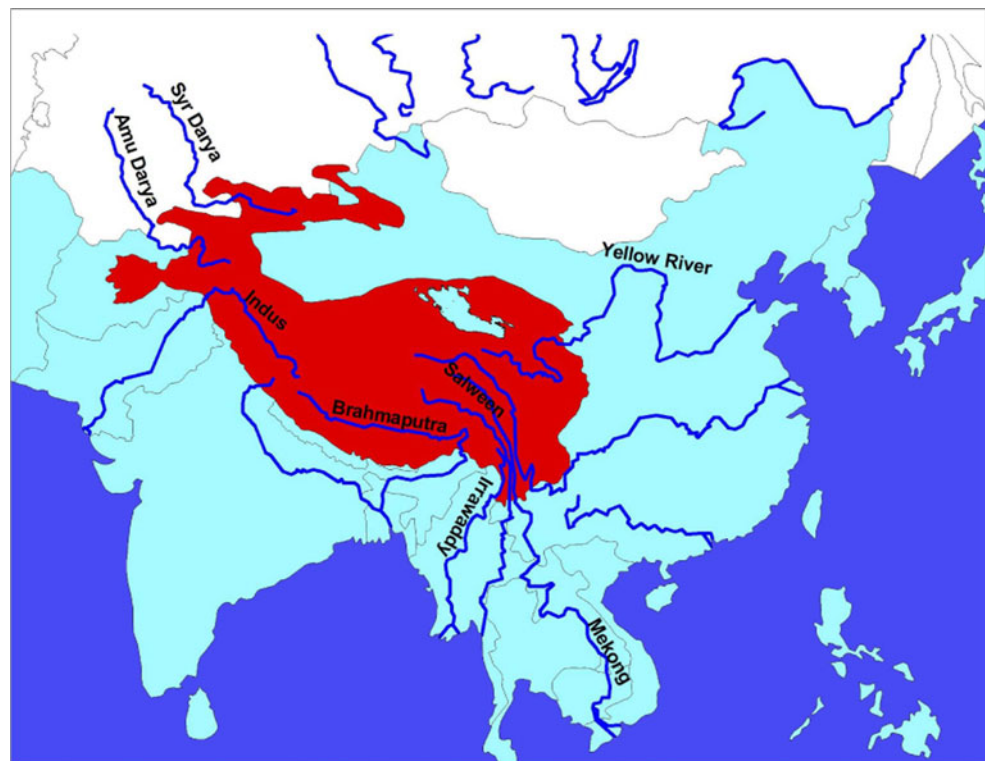
water for 25 % of the Chinese population in the dry season (Li et al. 2008; Xu et al. 2009).

Vegetation cover at high altitude has an impact on atmospheric circulation and water cycling through reflection rates on surface energy, wind drag, evaporation, and soil moisture. With almost 1.3 billion people living in river basins originating in the Himalayas, the hydrological importance of highland glaciers, wetlands, and other cryogenic features and their significant roles in regional hydrological processes have attracted much attention (Xu et al. 2009). The wetlands also play an important role in regulating these processes.

Data used

Srtm-dem

Digital elevation modeling (DEM) plays a pivotal role in delineating wetlands. A DEM can represent the water flow direction and provide indicators combined with other conditions for identifying and refining the wetland information extracted. A 90-m resolution shuttle radar topography mission (SRTM) DEM (downloaded from the Data-Sharing Network of Earth System Science http://www.geodata.cn) was used to register and refine wetland classification.

MODIS-imagery

In this study, we used MODIS/Terra Surface Reflectance imagery with 500 m spatial resolution for bands 1–7 (459–479, 545–565, 620–670, 841–876, 1,230–1,250, 1,628–1,652, and 2,105–2,155 nm, respectively) and 250 m spatial resolution for red (620–670 nm) and near infrared (841–876 nm) bands for wetland extraction.

Sixty-five images were selected as comparative images after examining more than 400 MODIS images downloaded in 2005. Using factors such as less snow cover, freedom from clouds, and coverage of the whole study area, 12 images distributed throughout autumn, winter, and spring were required. The output was compared because these images overlap in some areas. The images acquired cover the high-altitude region that extends from 24.73°N 69.45°E to 48.8°N 110.5°E (see Table 1). The region has an area of about 9.8 million km^2 that includes the Tibet, Yunnan, Sichuan, Qinghai, Gansu, and Xinjiang regions of China and the highlands of Nepal, Bhutan, India, Tajikistan, Kyrgyzstan, Kazakhstan, Uzbekistan, Afghanistan, Pakistan, and Myanmar. The images were obtained from the Tibet Meteorological Bureau MODIS Receiver in 2005.

Table 1 Monthly distribution of MODIS images selected in 2005

| Month	Compared images	Selected images
January	7	1
February	7	1
March	5	0
April	8	3
May	4	0
June	4	0
July	5	0
August	2	0
September	10	2
October	5	1
November	4	1
December	4	2
Total	65	12

Existing ecological maps (with the 4+ zones)

Image regionalization divides the study area into several relative homogeneous regions to reduce noise and to refine the extraction arithmetic for the geophysical complex landscape of the Himalayan region. The eco-geographic system (EGS) is a hierarchical, regional system combined with geographically related comparisons and integrated analysis of biological and non-biological factors on the earth's surface. The main objective of the system is to produce special patterns of natural factors and their relationship to natural resources. Wu et al. (2001) divided West China into eight temperature zones and 25 basic regions. There are many instances of regional variance. The regional physio-geographical system (RPGS) of the Himalayan–Tibetan Plateau (HTP) shows vertical differentiation at the edge of the HTP because of great disparity in height, but next to the lowlands the differentiation is horizontal. There are many mountains showing vertical differentiation inland but horizontal extension at the baseband (Zheng 1996). Therefore, the RPGS of the HTP mainly presents horizontal differentiation restricted by vertical zones. Zheng (1996) divided the Tibetan region into three temperature zones and 11 natural zones.

Combining the map of the eco-geographical system of western China, a map of the physical geography of Tibet, and collective image features, the research area was divided into three rough homogeneous regions:

1. Region I: southeast conifer, shrub, steppe humid and sub-humid region.
2. Region II: middle alpine desert, steppe cold and semi-arid region.
3. Region III: west montane steppe and meadow dry sub-humid region (see Fig. 2).
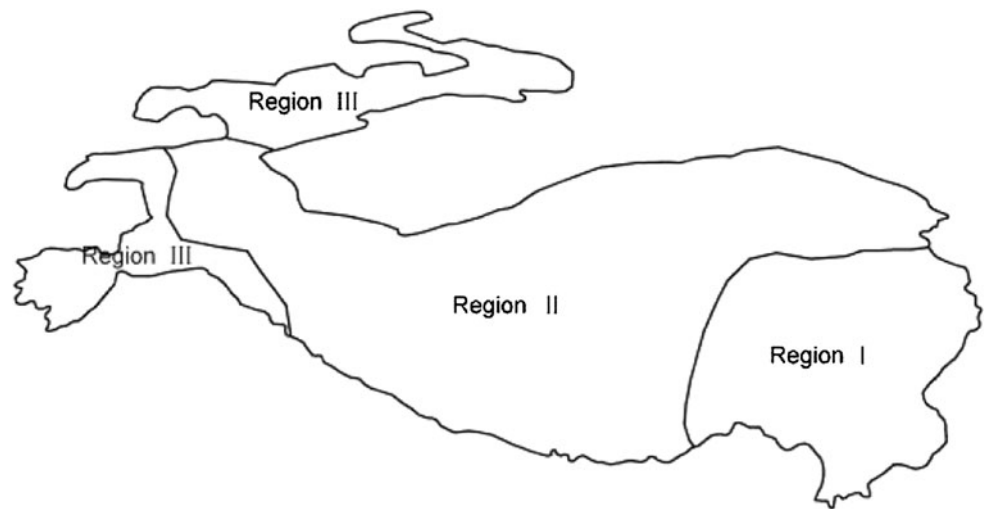
Methodology

The method framework is illustrated in Fig. 3. After image preprocessing and regionalization, wetland classification will be implemented using three indexes with slop map for each region. Specifically, water index (WI) with slope map is used to abstract water body; soil moisture index (SMI) and ratio vegetation index (RVI) with slope map are used to abstract flooded soil, marsh.

Extraction of flat areas

Image processing and classification were carried out using ERDAS Imagine (version 8.5). Area and conversion statistics were calculated using Microsoft Excel (2007). Field maps were produced using ARCGIS/ESRI (version 8.3).

A slope map generated from the DEM using ArcGIS software was used for wetland classification. To eliminate false changes to improve image contrast, and remove unclassifiable areas, a mask file was created consisting of topographic shadows, clouds, snow, and glaciers (Li et al. 2008). Once the mask file was created it was then applied to all images to equalize the total classifiable area between image dates. After each classification, there were small amounts of pixels that were unclassifiable for each image and these were added to the mask area. These areas were easily discernible and extracted from the MODIS image using a supervised classification process. Quality assurance data are provided for the individual pixel for each band and for the whole file, and they have been validated to define the uncertainties over a range of representative conditions. A smoothing filter was applied to all images prior to classification. This technique has been found to improve classification results by reducing spectral variability within classes and enhancing resolution between class separability (Tottrup 2004).

Classification with MODIS imagery

Wetland classification is often hierarchical. Generally, high-level dynamics show large-scale, low-frequency, slow-speed characteristics in the hierarchical system: in contrast, low-level activities or dynamics present small-scale, high-frequency and high-speed characteristics (Qiu et al. 2000; Xiao et al. 2003). The Ramsar classification system for wetlands provides criteria for classification in the field. A satellite image including both spectral and spatial information is often applied to extract wetlands on different scales, and this differs from traditional field inventories based on topographic maps. A hierarchical wetland classification was developed to map high-altitude wetlands based on the characteristics of moderate-resolution MODIS satellite images. There are two kinds of classification; viz., water bodies (lakes, rivers, pools, and floodplains) and marshes (soft, wet, low-lying and water-logged areas covered by grassy vegetation and often forming a transition zone between water and land).

A typical physical feature of wetlands is that vegetation grows on flooded soils. Water dominates the patterns and processes in wetland ecosystems. There are three types of wetland landscape at high altitude:

1. open water
2. flooded soil
3. vegetation grown on flooded soil or on the surface of open water.

In an open-water landscape, the vegetation that grows or floats on the surface of the water is limited, and satellite signals mainly absorb water-reflecting spectra. In a flooded soil landscape, humid soil is exposed on the land surface. Images absorb a mixture of water and soil-reflecting spectra. When vegetation is growing, parts of the open water and flooded soil are canopied by green plants.
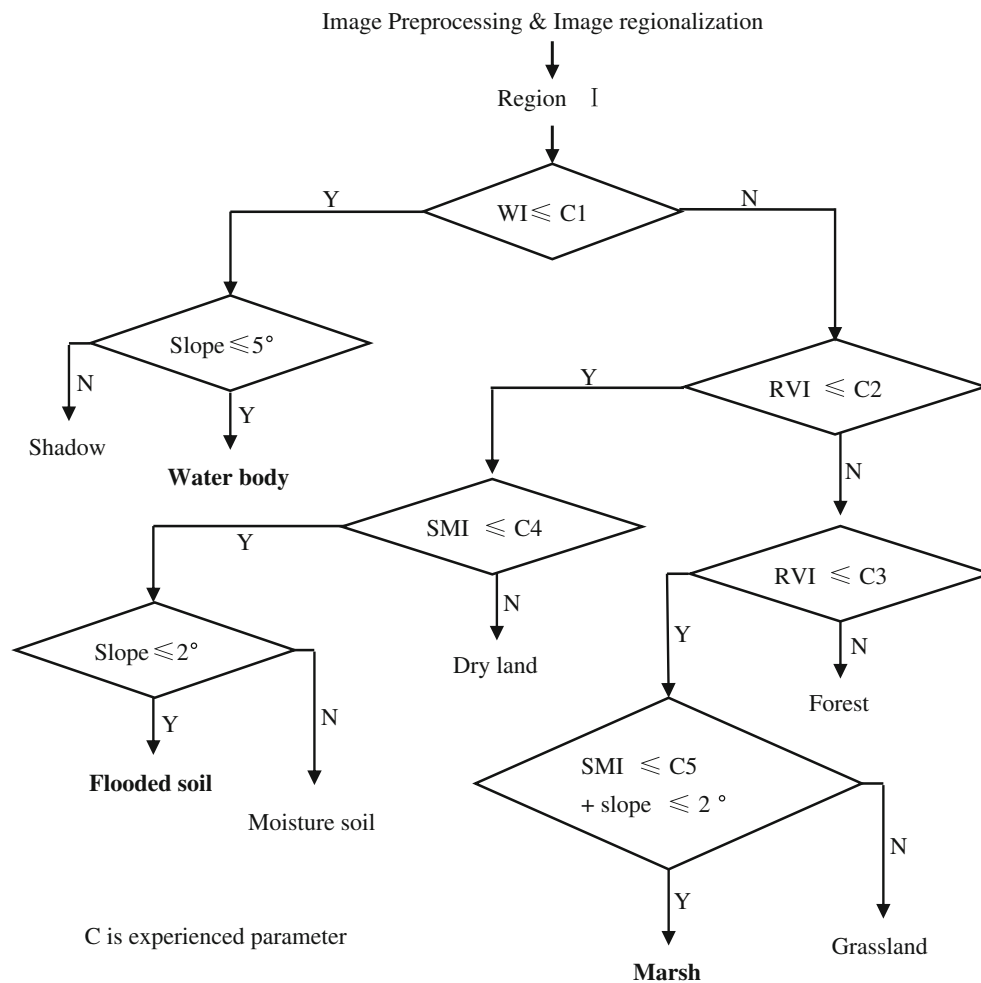
Image Preprocessing & Image regionalization

Region Ⅰ

Fig. 3 Image preprocessing and image regionalization

This study used a combination of unsupervised and supervised classification approaches to produce a final classification map for the entire Himalayan region. This hybrid method of remote-sensing classification with ecological characterization has been found in other studies to produce better results (Miller and Yool 2002). Training areas were used to extract spectral information for each known wetland cover from the images that were chosen on the basis of the local knowledge acquired during previous field trips to the study area. In addition, a Landsat satellite image acquired for other projects was used to select the training areas. This image was also used to assess the accuracy of the classification system.

In order to identify changes in the mixture of surface water, soil moisture, and green vegetation, spectral bands or vegetation indices sensitive to water, soil, and vegetation are required, as well as transformation to extract brightness, greenness, and moistness (Kauth and Thomas 1976). The calculations used water index [WI; Eq. (1)], soil

moisture index [SMI; Eq. (2)], ratio vegetation index [RVI, Eq. (3)], as follows.

$$WI = NIR_1 \times SWIR_1 = MODIS_{B2} \times MODIS_{B6} \qquad (1)$$

$$SMI = SWIR_1 \times SWIR_2 = MODIS_{b6} \times MODIS_{b7} \qquad (2)$$

$$RVI = \frac{NIR_1}{RED} = \frac{MODIS_{B2}}{MODIS_{B1}} \qquad (3)$$

· Water is the main absorber of sunlight. The 13 million tons of water in the atmosphere is responsible for about 70 % of all atmospheric absorption of radiation, mainly in near infrared radiation (NIR) and short wavelength infrared (SWIR) regions where water has a strong absorptive capacity (Zhao 2003). The SWIR spectral band is sensitive to leaf water and soil moisture and is used to develop improved vegetation indices that are sensitive to equivalent water thickness (Maki et al. 2004; Xiao et al. 2002a, b, 2006). The WI and SMI were developed and it was found that they are sensitive to water on the land surface. WI is

suitable for extracting open water and SMI is suitable for detecting flooded soil. RVI is a sensitive indicator of green plants, and it is correlated to leaf area index (LAI) and chlorophyll and is used to evaluate and monitor green plant biomass (Zhao 2003).

Field data and accuracy assessment

In lieu of a statistically based accuracy assessment, the final classifications for satellite images were examined carefully and compared against all available reference data (Li et al. 2007a; Pu et al. 2007; Cai et al. 2007). Field assessments using a geographical positioning system (GPS) were carried out on the Tibetan Plateau from 2005 to 2007. Accuracy assessment points were collected using a Garmin 'Summit' GPS connected to a HP Compaq hand-held computer running ESRI ArcPad software. This set-up facilitates easy and efficient collection of point coordinates and attributes such as land use, wetland type, and elevation. Attempts were made to spread the collection area of points along the highways throughout the Tibetan Plateau. However, due to the size of the region, time, and access constraints, a wide west to east spread was difficult to achieve. Where possible, points were recorded at least 500 m (1 pixel) from the land-cover type boundary. When points were recorded from a vehicle, information was included about distance to the boundary and land-cover class on either side of the road and so forth. The 461 samples were collected from the classification result at random: 127 samples were from water bodies, 234 samples from marshes, and 100 samples from non-wetland areas.

In summary, the hybrid model combines month-on-month, multispectral classifications from moderate resolution satellite (MODIS) data with a simple wetland extraction model based on knowledge of the characteristics of the spectrum and wetland ecology in high-altitude regions. The model was applied to the Tibetan Plateau using MODIS data. Compared with the best available sources for lakes and wetlands on global and national scales, and validated with high-resolution images, the authors found that the methodology gave satisfactory results. The total accuracy was as much as 70.91 %. Wetland information extraction shows that the model can extract wetlands in the Himalayan region automatically with minimal ground knowledge.

This model was further tested by adjusting parameters and applying them to high-resolution satellite data (Landsat) at sub-basin level. The high-altitude wetlands maps, generated from the proposed hybrid wetland extraction model, provide decision makers with salient information about the extent and distribution of high-altitude wetlands and their response to impacts of global warming and human activities. Hence, there is an urgent need to quantify these ecosystems through comprehensive mapping exercises for the benefit of planners and decision-makers.

Results

Wetland cover

The total area above 3,000 m is 3,846,131 km^2 and the area of wetland is 107,948 km^2 (2.81 %): this includes water bodies, of 61,627 km^2 (1.6 %) and marshes of 46,321 km^2 (1.2 %). The total area of China lying above 3,000 m is 291, 3,297 km^2 and the area of wetland is 96,329 km^2, accounting for 0.31 %: this includes water bodies 53,896 km^2 (1.85 %) and marshes 43,433 km^2 (1.46 %) (See Table 2; Fig. 4).

Figure 5 shows that high-altitude wetlands are located mainly at heights between 4,500 and 5,000 m, accounting for 50.1 % of the plateau and at the base of glacial distribution. Wetlands seldom occur above 6,000 m. There are more water bodies than marshes above 4,000 m, indicating that glacial melt provides immediate accumulation of water and vegetation produces less biomass and marshland. In contrast, there are more marshes below 4,000 m due to the abundant vegetation.

Proportion of wetland

Table 3 shows a large area of wetland coverage in the headwaters of the Yangtze (17,712 km^2) and Yellow rivers (16,413 km^2), followed by the Brahmaputra (8,850 km^2) and Salween (7,407 km^2). Arid basins such as the Indus and Tarim have more water bodies than marshes.

There is significant regional variation in wetland coverage in terms of wetland types and area covered as a result of variation in the climate and orographic influences. Predominated by water body, wetland cover is concentrated in region II (total 66,883 km^2, accounting for 62.2 %). Region I has a total area of 30,469 km^2 accounting for 28.2 % and is mostly made up of marshland. This region receives more precipitation and moisture than the others and hence has denser vegetation. Region III has an arid natural environment and the least wetland coverage (<10 %), and wetlands there mainly consist of water bodies (Table 4).

Table 2 Wetland area statistics of greater Himalayan region

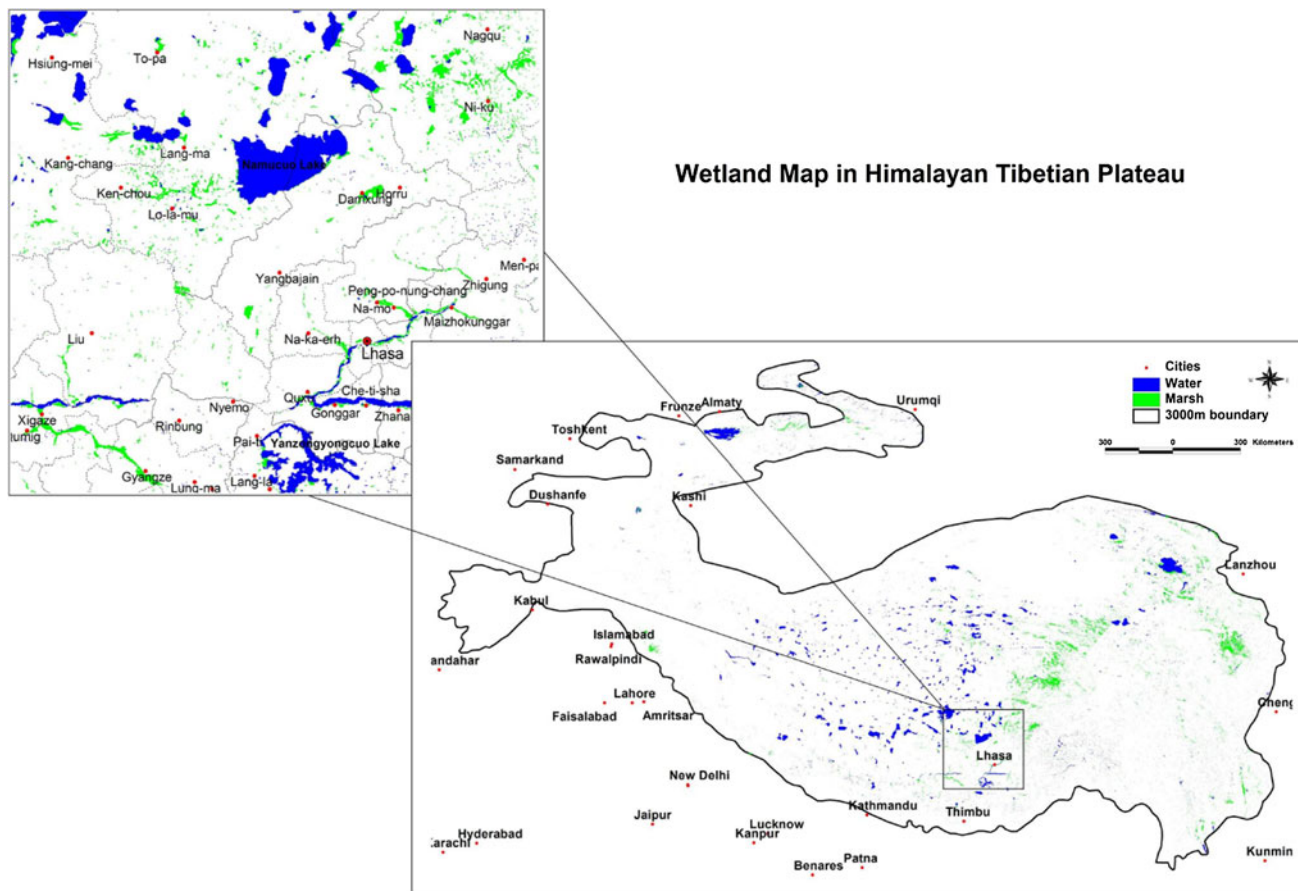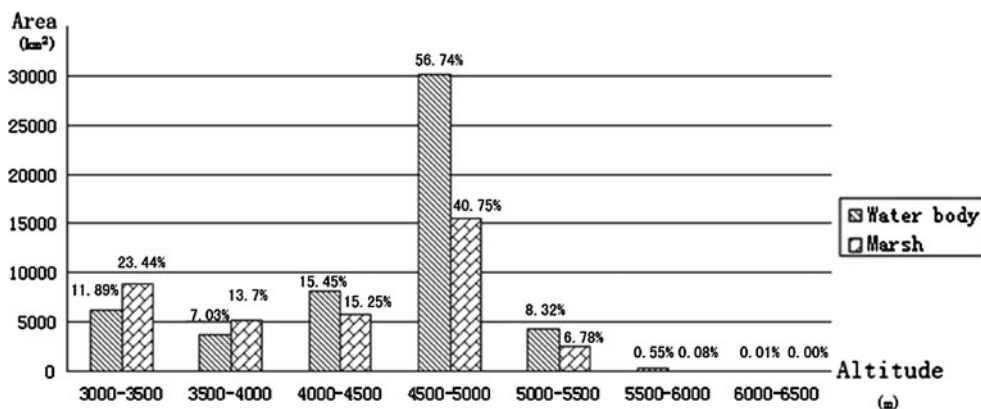| Greater Himalayan region	km^2	Wetlands (%)
Water bodies	61,627	1.6
Marshes	46,321	1.2
Total area above 3,000 m	3846131	2.81

Fig. 4 Wetland distribution map of the greater Himalayan region

Fig. 5 Wetland distribution according to altitude

Accuracy assessment

Kappa is 0.66 for the entire Himalayan region: 0.85 for water bodies and 0.54 for marshes (Table 5). From this evaluation, the classifications were deemed to be moderately accurate representations of the actual land-cover/land-use classes of the study region during the time periods covered.

Among the samples of misclassified water bodies, eight were shadow areas, six were dry lakes, and two were marshes. Among the samples of misclassified marshes, 53 were forests, 19 were dry grasslands, and eight were water bodies.

Discussion

Climate change and wetlands

Wetlands are sensitive ecosystems. The Himalayan wetlands are threatened by climate change as well as direct

Table 3 Wetland distribution in different watersheds (unit: km^2)

	Amu Darya	Indus	Ganges	Brahmaputra	Irrawaddy	Salween	Mekong	Yangtze	Yellow river	Tarim
Water Body	327	2,827	448	5,587	22	3,376	230	3,706	3,110	1,253
Marsh	121	1,150	500	3,264	25	4,031	1,389	14,006	13,303	298
Total	448	3,977	948	8,850	46	7,407	1,618	17,712	16,413	1,551

Table 4 Wetland distribution in different regions (unit: km^2)

Region	Region I (east)		Region II (mid)		Region III (west)	
	Area	%	Area	%	Area	%
Water body	6,899	11.2	47,517	77.1	7,212	11.7
Marshes	23,571	50.9	19,366	41.8	3,384	7.3
Total	30,469	28.2	66,883	62.0	10,596	9.8

Table 5 Accuracy assessment for wetland extraction

Reference class	Water body	Marshes	Non-wetland	Reference class total ΣPpi
Water bodies	108	2	17	127
Marshes	8	148	78	234
Non-wetland	0	0	100	100
Image class total ΣPli	116	150	195	461

human activities and it is likely that the existing regional wetland stock will be reduced substantially. These important ecosystems are often not found on land-cover maps of the region. In the absence of proper assessment, wetlands are being subjected to significant alteration. The impact will be particularly severe in certain regions: region I is subject to increasing human activity; region II to large-scale infrastructural development (e.g. the Qinghai–Tibet railway), and region III to climates that threaten to destroy the small wetlands through global warming. The authors found that climate change was a key factor in wetland distribution through precipitation patterns affecting recharge of both surface and underground water and evaporation transportation. Climate also determines aquatic vegetation, population dynamics, and hydrological and ecological processes; therefore, wetlands are very sensitive to climate change.

This mapping exercise could prove to be extremely beneficial for detecting changes in these ecosystems. Climate change at the levels projected will cause substantial cascade effects on high-altitude wetlands through changes in water-heat balance, drought-wet cycles, freezing and thawing alternation, and orographic disturbances. As temperatures change, the location of climate belts in the highlands will change. Permafrost currently covers about half of the highland area; but it is predicted to disappear, accelerating desertification. Some studies report changes in plant community structure, and in areas of permafrost and

wetland transition total loss of vegetation and ecosystem functions has been observed (Zhou et al. 2005). Decreases in water levels and degradation of wetlands in Qinghai Lake have been reported (Li et al. 2007b); this is mostly due to increasing evaporation and demands for water. The sacred Tibetan lake, Namcuo, grew by 38.15 km^2 (2 %) from 1970 to 2000 due to glacial melt (Wu and Zhu 2008),and glacial coverage decreased by 22.1 km^2 (11.3 %) in the Namcuo catchment. The Ruoergai wetland complex covers a total area of 16,000 km^2 and includes 4,900 km^2 of peat land with storage estimates varying between 1 and 4 billion tons. This area is undergoing one of the worst degradations of wetland and grassland in recorded history (Wang et al. 2002). With extreme variations in precipitation, desertification occurred (Wilkes 2008). Chen et al. (2008) reported a significant increase in methane emissions as well as spatial and temporal variations in the Ruoergai wetlands. This will have substantial impact on atmospheric chemistry and climate. Degradation of the Himalayan wetlands could transform them from carbon sinks to carbon sources.

Wetlands and grassland productivity

Alpine grassland productivity is highly correlated with precipitation and wetlands. Remote sensing of the Tibetan Plateau shows that the grasslands have benefited from global warming (Luo et al. 2004). Changes in the

normalized difference vegetation index (NDVI) (a proxy indicator for vegetation cover) across the plateau between 1982 and 1999 suggests that grassland cover has benefited from climate change due to an earlier onset of the growing season in spring and accelerated growth during the growing season due to higher spring temperatures (Yang and Piao 2006). Yang and Piao noted, however, that different responses occurred in different vegetation types with a lagged correlation with precipitation and that wetlands might play a key role in maintaining soil moisture and humidity.

The complex variations in climate change and wetlands across the Himalayan region are still unknown. Most wetland studies have focused on the eastern Tibetan Plateau, while there is little comparable research elsewhere in the Himalayan region. The eastern Tibetan Plateau is generally an area of comparatively denser rainfall and more productive vegetation types, but in recent decades it has also been subjected to warming and drying trends. Several studies of this region suggest that changes in temperature in the germination season in spring and during autumnal decay, as well as decreases in summer precipitation, are having adverse effects on wetlands and grasslands (Yu et al. 2010). Scientific studies are not the only source of information on the impacts of climate change on wetlands and grasslands in the three rivers' source area.

One anthropological study (Zhang and Li 2005) reported that among 200 herders interviewed in the Yangtze river source area, almost 85 % reported obvious climate changes and more than 55 % reported obvious impacts on the grasslands such as changes in precipitation (15 %), changes in grass quality (13 %), changes in grassland area (10 %), and changes in frequency of animal disease epidemics (13 %). The vast majority of herders agreed that there is a link between climate change and degradation or desertification of wetlands and grasslands. Highland herders were found to be more sensitive to climate change in the warm season than in the winter because the warm season is the growth period for the grasslands on which their livestock depend. Herders reported that, in the past, the warm season lasted for 3–4 months, but now it lasts for <3 months.

Late growth of the grasslands has had a huge impact on livestock growth, calving or lambing, and milking. The impact of climate change on the grasslands are thus of direct relevance to animal husbandry and the livelihoods of herding communities.

Uncertainties and limitations of the current mapping exercise

The limitations associated with using remote-sensing data in mountainous areas are well documented: cloud and snow cover, topographic shadow, steep slopes, and difficulty of access for field work are common (Shrestha and Zinck 2001). The MODIS images more difficult to classify are those affected by cloud cover, particularly during monsoon. In addition, this study was restricted by the lack of independent reference data for accuracy assessment. The Himalayan wetlands are transitions between land, grass, and water and can be ephemeral or permanent. The other obvious limitations in capturing wetland cover of the Himalayan landscape include the natural diversity, geographic complexity, and changing human-induced impacts.

Moderate resolution (250 m–1 km) land-cover products often underestimate areas of land cover due to the fragmentation and sub-pixel proportions of individual land-cover types (Xiao et al. 2006). Digital elevation models (DEM) play an important role in this method. We used an SRTM-DEM resolution of 90 m; but a higher resolution will bring better results.

This exercise has shown, however, that land cover can be fairly well assessed and relatively reliable results produced with remote-sensing technology. As an alternative, we used higher resolution satellite images to assess the accuracy of both location and area coverage. Area coverage is more challenging because of seasonal changes in the wetlands. Two hypotheses were tested for accuracy assessment. One was that the spectrum used can represent wetland areas sufficiently by using remote-sensing techniques and it is not essential to do an accuracy assessment of the area. The other is that wetlands can be identified more accurately using visual interpretation of TM (thematic map) images. The identification of wetlands can be carried out automatically by machine with the variables used in this paper; viz., DEM, slope, temperature, and ecological factors. All these factors can be converted into raster formats and can be used as inputs for a classifier. For wetland classification, an object-based classifier might be more suitable as it can incorporate all potential factors. As such, visual inspection/interpretation could be replaced by automatic recognition.

An understanding of the spatial coverage of the wetlands is vital for monitoring the Himalayan wetlands. With the daily availability of MODIS images, the hybrid method we developed can provide temporal dynamic analyses of wetland cover in the region. The uncertainty of wetland mapping can be reduced through further studies:

1. seasonal variation;
2. overall regional trend, and
3. anthropogenic impacts through land-use/land-cover change.

It is recognized that regional assessment is useful but not comprehensive enough for understanding the ecological and hydrological dynamics of wetland complexes, and

between the highlands and lowlands. Long-term monitoring, networking, open data exchange, and transboundary cooperation in the Himalayas are indicated to address data gaps to promote a better understanding of high-altitude wetland conservation.

Conclusion

Clearly, wetland cover is a vital component of the Himalayan landscape. Wetlands are very sensitive to climate change due to their transitional nature. The recent fluctuations in the high-altitude wetlands in the Himalayas and on the Tibetan Plateau due to global warming are substantial. The region will face increasing water shortages and carbon emissions if the wetlands deteriorate further. A spatial information system is urgently needed for rapid assessment and continued monitoring of the performance of high-altitude wetlands as an indicator of environmental change in the Himalayas.

The Himalayan region will also face water shortages in the long term due to the loss of the wetland buffer. However, this will not prevent expansion of wetlands in certain areas. Degradation of headwater wetlands in Sanjiangyuan (three river headwaters) will exacerbate droughts in the catchment areas of rivers such as the Yangtze, and the Mekong where there is rapid population growth and dependency on water resources from high-altitude wetlands.

References

An SQ, Li HB, Guan BH, Zhou CF, Wang ZS, Deng ZF, Zhi YB, Liu YH, Xu C, Fang SB, Jiang JH, Li HL (2007) China's natural wetlands, past problems, current status, and future challenges. Ambio 36(4):335–342

Barnett TP, Adam JC, Lettenmaier DP (2005) Potential impacts of a warming climate on water availability in a snow-dominated region. Nature 438(17):303–309

Cai DH, Guo N, Han T (2007) Dynamically monitoring the high-cold swamp and wetland in 1990–2001 in Maqu by means of remote sensing. J Glac Geoc 29(6):874–881 (in Chinese with English abstract)

Chalise SR, Khanal NR (2001) An introduction to climate, hydrology and landslide hazards in the Hindu Kush-Himalayan region. In: Tianchi L, Chalise SR, Upreti BN (eds) Landslide Hazard Mitigation in the Hindu Kush-Himalayas, Kathmandu, ICIMOD, pp 51–62

Chen YN, Takeuchi K, Xu CC, Chen YP, Xu ZX (2006) Regional climate change and its effects on river runoff in the Tarim Basin, China. Hydrol Process 20:2207–2216

Chen H, Yao SP, Wu N, Wang YF, Luo P, Tian JQ, Gao YH, Sun G (2008) Determinants influencing seasonal variations of methane emissions from alpine wetlands in Zoige Plateau and their implications. J Geophys Res 113:D12303. doi:10.1029/2006JD008072

Frield MA, McIver DK, Hodges JCF, Zhang XY, Muchoney D, Strahler AH, Woodcock CE, Gopal S, Schneider A, Cooper A, Baccini A, Gao F, Schaaf C (2002) Global land cover mapping from MODIS: algorithms and early results. Remote Sens Environ 83:287–302

ICIMOD, WWF & Ramsar (2003) Report of the regional workshop on Wetland conservation and wise use in the Himalayan high mountains. Kathmandu, Nepal (Unpublished)

Kauth RJ, Thomas GS (1976) The tasseled cap—a graphic description of the spectral-temporal development of agricultural crops as seen by Landsat. In: Proceedings of the symposium on machine processing of remotely sensed data. Indiana, LARS, Purdue University Lab. App Remote Sensing West Lafayette, pp 41–51

Lehner B, Doll P (2004) Development and validation of a global database of lakes, reservoirs and wetlands. J Hydrol 296:1–22

Li ZQ, Yu GR, Xiao XM, Li YN, Zhao XQ, Ren CY, Zhang LM, Fu YL (2007a) Modeling gross primary production of alpine ecosystems in the Tibetan Platean using MODIS images and climate data. Remote Sens Environ 107:510–519

Li XY, Xu HY, Sun YL, Zhang DS, Yang ZP (2007b) Lake level change and water balance analysis at Lake Qinghai, West China, during recent decades. Water Resour Manag 21:1505–1516

Li X, Cheng G, Jin H, Kang S, Che T, Jin R, Wu L, Nan Z (2008) Cryospheric change in China. Glob Planet Change 62:210–218

Luo TX, Pan Y, Ouyang H, Shi PL, Luo J, Yu ZL, Lu Q (2004) Leaf area index and net primary productivity along subtropical to alpine gradients in the Tibetan Plateau. Glob Ecol Biogeogr 13:345–358

Maki M, Ishiahra M, Tamura M (2004) Estimation of leaf water status to monitor the risk of forest fires by using remotely sensed data. Remote Sens Environ 90:441–450

Miller JD, Yool SR (2002) Mapping forest post-fire canopy consumption in several overstorey types using multi-temporal Landsat TM and ETM data. Remote Sens Environ 82:481–496

Owen LA, Finkel RC, Caffee MW (2002) A note on the extent of glaciation throughout the Himalaya during the global last glacial maximum. Quat Sci Rev 21:147–157

Ozesmi SL, Bauer ME (2002) Satellite remote sensing of wetlands. Wet Ecol Manag 10(5):381–402

Pu ZX, Xu L, Salomonson VV (2007) MODIS/Terra observed seasonal variations of snow cover over the Tibetan Plateau. Geophys Res Lett 34:L06706. doi:10.1029/2007GL029262

Qiu Y, Zhang J, Zheng F (2000) The Kernel of landscape ecology, spatial and temporal heterogeneity in ecological systems. Chin J Ecol 19(2):42–49 (in Chinese)

Ramsar (2002) Ramsar resolution VIII. 30, http://www.ramsar.org/key_res_viii_30_e.doc Accessed 27 Oct 2008

Shrestha DP, Zinck JA (2001) Land use classification in mountainous areas, integration of image processing, digital elevation data and field knowledge (application to Nepal). Int J Appl Earth Obs Geoinf 3(1):78–85

Singh P, Bengtsson L (2004) Hydrological sensitivity of a large Himalayan basin to climate change. Hydrol Process 18:2363–2385

Smith LC (1997) Satellite remote sensing of river inundation area, stage, and discharge: a review. Hydrol Process 11:1427–1439

Tottrup C (2004) Improving tropical forest mapping using multi-date Landsat TM data and pre-classification image smoothing. Int J Remote Sens 25(4):717–730

Wang GX, Qian J, Cheng GD, Lai YM (2002) Soil organic carbon pool of grassland soils on the Qinghai-Tibetan Plateau and its global implication. Sci Total Environ 291:207–217

Wang ZS, Zhou CF, Guan BH, Deng ZF, Zhi YB, Liu YH, Chi X, Fang SB, Xu Z, Yang HB, Liu FD, Zheng JW, Li HL (2006) The headwater loss of the western plateau exacerbates China's long thirst. Ambio 35(5):271–272

Wilkes A (2008) Towards mainstreaming climate change in grassland management, policies and practices on the Tibetan Plateau. ICRAF Working Paper No. 67. Nagarjuna Publications, Kathmandu

Winiger M, Gumpert M, Yamout H (2005) Karakoram-Hindu Kush-western Himalaya, assessing high-altitude water resources. Hydrol Process 19(12):2329–2338

Wu YH, Zhu LP (2008) The response of lake-glacier variations to climate change in Nam Co Catchment, central Tibetan Plateau, during 1970–200. J Geogr Sci 18:177–189

Wu SH, Zheng D, Yang Q (2001) A preliminary study on eco-geographic system and ecological construction in west China. Prog Geog Sci 20(1):10–20

Wu HB, Guo ZT, Peng CH (2003) Distribution and storage of soil organic carbon in China. Global Biogeochem Cy 17(2):1–11

Xiang S, Guo R, Wu N, Sun SC (2009) Current status and future prospects of Zoige Marsh in eastern Qinghai-Tibet Plateau. Ecol Eng 35:553–562

Xiao X, Boles S, Frolking S, Salas W, Moore B, Li C, He L, Zhao R (2002a) Landscape-scale characterization of cropland in China using vegetation and Landsat TM images. Int J Rem Sens 23:3579–3594

Xiao X, Boles S, Frolking S, Salas W, Moore B, Li C, He L, Zhao R (2002b) Observation of flooding and rice transplanting of paddy rice fields at the site to landscape scales in China using VEGETATION sensor data. Int J Rem Sens 23:3009–3022

Xiao D, Li X, Gao J, Chang Y, Li S (2003) Landscape Ecology. Science Press, Beijing

Xiao XM, Boles S, Frolking S, Li CS, Babu JY, Salas W, Moore B (2006) Mapping paddy rice agriculture in south and southeast Asia using multi-temporal MODIS images. Remote Sens Environ 100:95–113

Xu JC (2007) The Highlands, a shared water tower in a changing climate and changing Asia. ICRAF Working Paper 64. http://worldagroforestry.org/our_products/publications/details?node=50695

Xu ZX, Chen YN, Li JY (2004) Impacts of climate change on water resources in the Tarim river basin. Water Res Manag 18:439–458

Xu JC, Grumbine ED, Shrestha AB, Eriksson M, Yang XF, Yang Y, Wilkes A (2009) The melting Himalayas, cascade effects of climate change on water resources and human livelihoods in the greater Himalayas. Conserv Biol 23(3):520–530

Yang YH, Piao SL (2006) Variations in grassland vegetation cover in relation to climatic factors on the Tibetan Plateau. J Plant Ecol 30(1):1–8

Yu HY, Luedeling E, Xu JC (2010) Winter and spring warming result in delayed spring phenology on the Tibetan Plateau. P Natl Acad Sci USA 107(51):22151–22156

Zhang J, Li Y (2005) Impact of climate change on the Yangtze River source region in Tibetan Plateau. Himal Cent Asian Stud 9(4):47–62

Zhang XY, Friedl MA, Schaaf CB, Strahler AH (2004) Climate controls on vegetation phenological patterns in northern mid-and high latitudes inferred from MODIS data. Glob Change Biol 10:1133–1145

Zhao YS (2003) The theory and method for application and analysis of remote sensing. Science Press, Beijing

Zheng D (1996) The system of physico-geographical regions of the Qinghai-Tibet Plateau. Sci China 39(4):410–417

Zhou W, Chen BK (2006) Biodiversity of Bitahai nature reserve in Yunna province, China. Biodivers Conserv 15(3):839–853

Zhou HK, Zhao XQ, Tang YH, Gu S, Zhou L (2005) Alpine grassland degradation and its control in the source region of the Yangtze and Yellow rivers. China Grassl Sci 51(3):191–203