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# Impact of the construction of a large dam on riparian vegetation cover at different elevation zones as observed from remotely sensed data

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ABSTRACT

The impact of the construction of a large dam on riparian vegetation cover can be multifold. How the riparian vegetation cover changes at different elevation zones in response to the construction of a large dam and the subsequent impound of reservoir water is still an open question. In this study, we used satellite remote sensing data integrated with geographic information system (GIS) to monitor vegetation cover change at different riparian elevation zones on a large spatial scale, taking the Three Gorges Dam in China as an example. Due to the large scale of this newly formed reservoir, it is expected to impact the riparian vegetation canopy both directly and indirectly. We chose to monitor vegetation cover changes along the 100 km riparian stretch of river directly upstream of the Three Gorges Dam site, over the construction period of eleven years (2000–2010), using MODIS vegetation indices products, digital elevation model (DEM) data from ASTER, and the time series water level data of the Three Gorges reservoir as the data sources. Results show that non-vegetated area increased in the inundated zone (below 175 m), as expected; area of densely vegetated land cover increased within the elevation zone of 175–775 m and no change in vegetation cover was observed above 775 m in elevation. Regression analysis between the vegetation index data and the reservoir water level shows that increasing water levels have had a negative impact on vegetation cover below 175 m, a positive impact on vegetation cover is limited to the region between 175 and 775 m, and no significant impact was observed above 775 m. MODIS EVI product is less sensitive in mapping non-vegetated land cover change, but more sensitive in mapping vegetated land cover change, caused by the reservoir water level variation; both products are similar in effectively tracking a trend between land cover change in each elevation zone with time or with reservoir water level.

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## Introduction

As the global demand for energy, especially renewable energy increases, a surge in large dam projects for hydropower production is expected since hydropower is one of the most economic energy resources and is renewable through hydrological cycle along with its other benefits such as water supply, irrigation, flood control, navigation, and recreation (International Hydropower Association, 2000; DOE, 2004). In the case of large dams, it is imperative to understand the interactions between the uncertainty around and the significance of environmental impacts due to such large dams, because changes in terrestrial ecosystems can affect climate, soils, vegetation, water resources and biodiversity; which are all closely linked to the sustainability of socio-economic development (He et al., 2003; Tullos, 2009).

China has an extensive history of water resource development and is home to almost half (22,000 out of an estimated 45,000) of the world's large dams (Fuggle et al., 2000). The Three Gorges Project is the largest water conservancy project ever undertaken, with a total reservoir storage capacity of 39.3 billion $m^3$ (Hayashi et al., 2008). The Three Gorges Dam, with a length of 2335 m and a height of 185 m, is the largest dam ever built in China (Fu et al., 2010). It is a multi-purpose hydro-development project designed to yield comprehensive benefits in flood control, power generation, and navigation (Wang, 2002). The project first began to impound water in 2003 and came to completion when the desired maximum reservoir water level of 175 m was reached in 2009. At a water level of 175 m with a storage capacity of 39.3 billion $m^3$, the Three Gorges reservoir has a surface water area of over 1080 $km^2$. The Three Gorges Project has great potential for hydro-electrical power generation and flood control (Liu et al., 2004), but its possible impact

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on the environment and socio-economy needs to be quantified. Because building up of reservoirs will inevitably result in significant loss of upstream terrestrial habitat through inundation, riparian and terrestrial ecosystems will be more or less disturbed (Railsback et al., 1991). Similar situations have existed with the construction of the Bhakra and Hirakud Dams in India, Volta Dam in Ghana, Kariba Dam in Zambia and the Aswan Dam in Egypt. However, a wide range of problems exist, such as reservoir sedimentation, environmental degradation, migration and resettlement (Sahin and Kurum, 2002; Gao and Mao, 2009). The construction of the Three Gorges Dam is expected to have a great influence on all ecosystems involved (Subklew et al., 2010) and the impact on environment is expected to be multifold. The purpose of this study is to investigate and quantify the impact of the construction of the Three Gorges dam on the riparian vegetation cover at different elevation zones using long-term remotely sensed data.

Many large ecosystems associated with large dam reservoirs are difficult to monitor because they are in remote or poorly accessible areas. The traditional ground-based method used at the regional-scale is very difficult to implement due to costs, labor and time involved. Satellite remote sensing techniques provide a useful and the most economical means for the monitoring of vegetation productivity and terrestrial ecosystems, due to the availability of high spatial and temporal resolutions. Moreover, satellites provide consistent repeat images of the same area at different times, allowing for timely and consistent estimates of changes in vegetation dynamics and productivity, and subsequently trends of change in the vegetation cover over a long time scale and on a large spatial scale (Zeng et al., 2008; Bellone et al., 2009; Sun et al., 2009). The capacity to monitor any on-going changes is critical to efforts toward balancing sustainable resource management and responsible habitat conservation. These changes will have characteristic spatial, spectral, and temporal patterns that can be observed in multiple acquisitions of satellite data over time (Hayes and Cohen, 2007).

Since the Three Gorges dam was built in a topographically rough region, how elevation will constrain the scale on which the dam will impact the riparian vegetation is still an open question. We hypothesize that local steep topography may act as a barrier to the transport of moisture in the atmosphere of the microclimate regime surrounding the reservoir. To test this hypothesis, we subdivide the riparian region along the Yangtze river around the Three Gorges dam into multiple elevation zones and track the vegetation cover changes with time at each zone. The objectives of this study are: (1) to map the dam's impact on the spatial and temporal vegetation coverage at each elevation zone using remotely sensed vegetation indices data at a regional scale in the Three Gorges Dam riparian region; and (2) to investigate the change of vegetative canopy at each elevation zone in response to dynamic reservoir water levels.

## Study area

The Three Gorges Dam region in this study is the area from Baidicheng in Fengjie prefecture, Chongqing city, to Sandouping in Yichang prefecture, Hubei province (Hayashi et al., 2008). With a total length of 6300 km, the Yangtze River, the third longest river in the world, originates in the Tibet Plateau and flows eastward to the East China Sea. As the river flows east through the Daba mountains, it encounters a series of narrow constrictions at the Three Gorges of Qutang, Wu, and Xiling. The Three Gorges Dam was constructed at Sandouping in Yichang prefecture, Hubei province, located downstream from the Xiling Gorge. The area inundated by the reservoir pool stretches from Yichang of Hubei Province upstream to Jiangjin City of Chongqing Municipality, a distance of 600 km and covering an area of 57,900 $km^2$, including 9777 $km^2$ of previously cultivated land (Ponseti and López-Pujol, 2006). As a result of the dam construction, the average width of the upstream waterway increased from 0.6 to 1.6 km (Wu et al., 2006). The reservoir has a mean depth of about 70 m and a maximum depth near the dam of approximately 175 m. As the topographic profiles are narrow and deep, the reservoir will retain the long narrow belt shape of the original river section and will be a typical river channel-type reservoir. The Three Gorges region has a humid subtropical climate with a frost free season of 300–340 days. The mean annual temperature is 16.5–19.0 °C. Annual precipitation averages approximately 1100 mm, 80% of which is received from April to October (Chen, 1993). The Three Gorges area is a mountainous region with 95% of the area consisting of hills and mountains and only 4.3% being flatland (Chen and Wang, 2010). Elevations vary greatly in the study area, with the lowest elevations at approximately 60 m above sea level (asl) along the Yangtze River and the highest elevations averaging 2000 m (asl), with several mountain peaks reaching approximately 3000 m (asl). Natural vegetation along the main channel of the Yangtze River consists mostly of shrublands and grasslands (Jiang et al., 2005. Also please see Fig. 11).

This study focuses on the 100 km riparian stretch of river upstream of the Three Gorges Dam site within the Yangtze River catchment watershed boundary (Fig. 1). The straight line which makes up the western boundary of the study area indicates the 100 km mark upstream from the dam site. This 100 km riparian stretch of river was chosen as the study area because it includes the main body of the reservoir immediately above the dam, extensive reaches of newly flooded river corridor and tributaries as well as a wide range of elevations above the maximum reservoir level. The size of the study area allows for an appropriate portrait of how the environment is reacting to the new reservoir storage levels at a regional scale.

## Data sources

The data sources for this study include: 16-day 250 m vegetation indices satellite imagery data of Moderate Resolution Imaging Spectroradiometer (MODIS) on board Terra satellite; digital elevation model (DEM) data from Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), and the Three Gorges Reservoir water level data collected by China Three Gorges Corporation.

### *MODIS vegetation index products*

MODIS is one of the main instruments on board the Terra satellite launched in December 1999 and Aqua satellite launched in 2004. MODIS has a total of 36 bands, including 7 land bands. Out of the 7 land bands, two bands have a spatial resolution of 250 m and the rest have a spatial resolution of 500 m. The two 250 m bands were included to detect anthropogenic-driven land cover changes that commonly occur at or near this spatial scale (Townshend and Justice, 1988). Hansen et al. (2002) discovered that land cover changes associated with anthropogenic and natural causes can be well detected in the MODIS 250 m imagery. Wessels et al. (2004) and Wardlow et al. (2007) both found that general land cover patterns (e.g., agricultural, deciduous/evergreen forest, and grassland) could be successfully mapped with the MODIS 250 m data. MODIS has a total of 44 data products that hold the promise of becoming the most important data source for land cover characterization and operational monitoring at regional and global scales (Hayes et al., 2008). The land products from MODIS are designed to support long-term global change research and natural resource application (Justice et al., 2002).

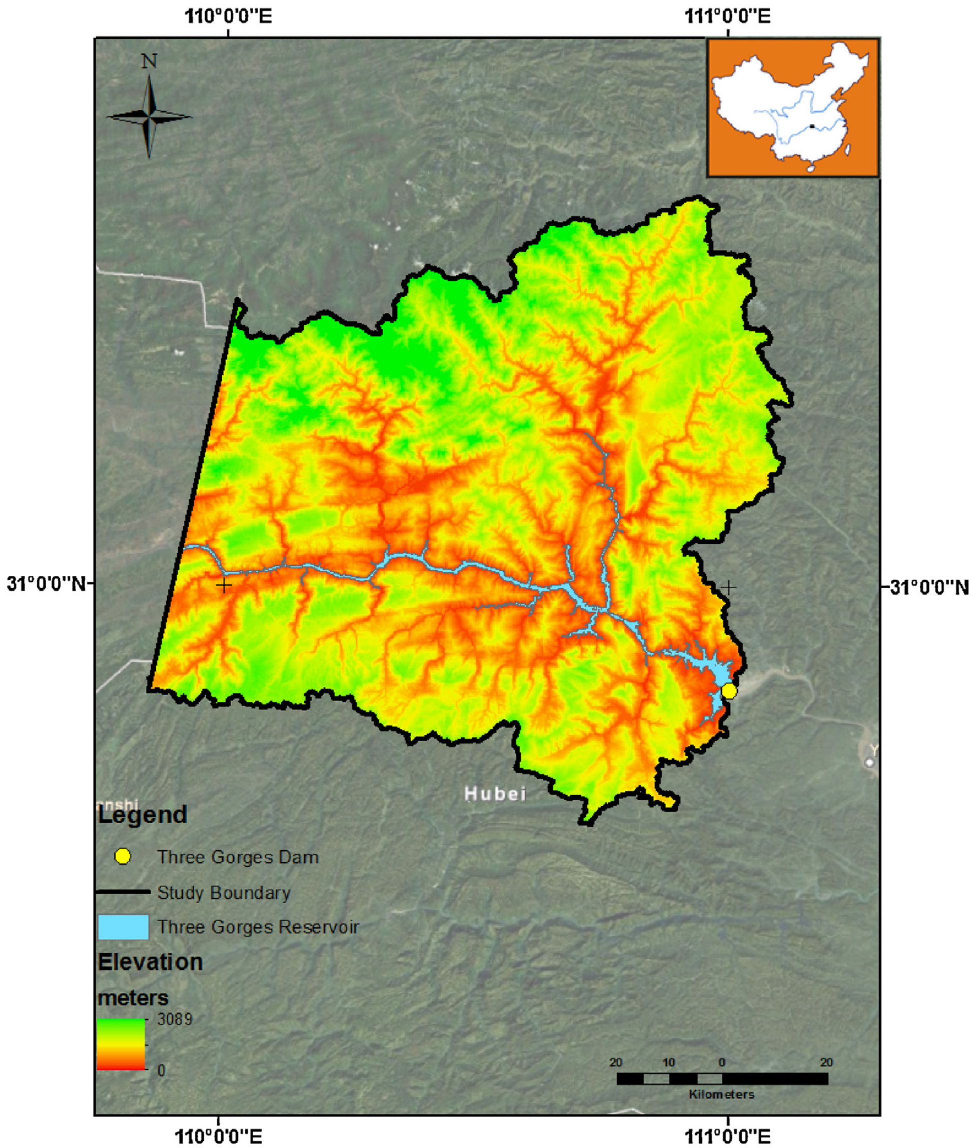


**Fig. 1.** Study area map. The study area stretches from the Three Gorges (shown by a yellow circle) upstream 100 km. The study area is bounded by the Yangtze River watershed (outlined in black). The inset is the outlined map of China indicating the location of the study site. Black square on the outlined map of China indicates the location of the study site. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Vegetation index (VI) is a measure of vegetation cover on the earth surface using band combinations from satellite imagery that correspond to different regions of the electromagnetic spectrum. Vegetation response to the electromagnetic spectrum is influenced by such factors as differences in chlorophyll content, nutrient levels, water content, and underlying leaf structure (Sivanpillai et al., 2006). The MODIS VI products provide a consistent spatial and temporal coverage of vegetation conditions and complement each other for vegetation studies (Huete et al., 2002). The MODIS MOD13Q1 products consist of two vegetation measurements: Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI). These two VIs complement each other in vegetation studies and improve upon the detection of land cover changes and extraction of canopy biophysical parameters. NDVI is a spectral-reflectance based index that is calculated by

$$\mathrm{NDVI} = \frac{\rho_{\mathrm{NIR}} - \rho_{\mathrm{red}}}{\rho_{\mathrm{NIR}} + \rho_{\mathrm{red}}} \tag{1}$$

where $\rho_{\mathrm{NIR}}$ and $\rho_{\mathrm{red}}$ are the bidirectional spectral reflectance at near-infrared (NIR) and red bands, respectively (Rouse, 1973; Zhou et al., 2009). For MODIS NDVI products, NDVI is calculated using the spectral reflectance of band 1 at NIR (841–875 nm) and band 2 at the red band (620–670 nm). NDVI values range from −1.0 to 1.0. Clouds, water, snow, ice and non-vegetated surfaces have NDVI values below 0.3. The NDVI values for vegetation are positive and most often range from 0.3 to 0.8, with lower values indicating sparse vegetation or poor vegetation conditions (Bellone et al., 2009). High NDVI value results from the absorption of red radiation by chlorophyll and other leaf pigments and the strong scattering of near-infrared radiation by foliage. As a consequence, red reflectance tends to decrease as the amount of green vegetation in a pixel increases; at the same time the structural properties of a denser or healthy canopy cause an increase in near-infrared reflectance. The NDVI quantifies the red-NIR contrast and has shown consistent correlation with vegetation biomass and vegetation dynamics in various ecosystems, such as the leaf-area index, the fraction of photosynthetically active radiation absorbed by vegetation and Net Primary Productivity (NPP) (Beck et al., 2006). Therefore, it is an indicator of vegetation vigor, health, and density. Thus this index is able to detect and measure land vegetation/degradation processes which may be defined as a long-term increases/loss of ecosystem function and productivity (Bellone et al., 2009). Variability in a vegetation index between dates can be used for monitoring vegetation changes.

EVI is a spectral reflectance based index that is calculated by

$$\mathrm{EVI} = G\frac{\rho_{NIR} - \rho_{red}}{\rho_{NIR} + C_1\rho_{red} - C_2\rho_{blue} + L} \quad (2)$$

where the $\rho$ values are partially atmospherically corrected (Rayleigh and ozone absorption) surface reflectance, $L$ is the canopy background adjustment ($L = 1$), $C_1$ and $C_2$ are coefficients of the aerosol resistance term that uses the blue band (458–479 nm) of MODIS (Huete et al., 1997) to correct for aerosol influences in the red band ($C_1 = 6$ and $C_2 = 7.5$), and $G$ is a gain factor ($G = 2.5$) (Huete and Liu, 1994; Huete et al., 1997). EVI is designed to minimize the effects of the atmosphere and canopy background that contaminates the NDVI by subtracting reflectance in the blue band from the NDVI and to enhance the green vegetation signal (Huete et al., 1997, 2002; Hayes et al., 2008). Gao et al. (2000) found that NDVI was more chlorophyll sensitive and can become saturated at high biomass levels. EVI is more responsive to canopy structure variations (e.g., LAI, plant physiognomy, and canopy type) and has improved sensitivity over high biomass areas (Wardlow et al., 2007). Unlike NDVI values which range from −1.0 to 1.0, EVI values range from 0, indicating no vegetation, to 1, indicating densest vegetation.

MOD13Q1 is a 16-day composite VI dataset with 250 m spatial resolution. The data sets used for this study span the period from the start to completion of the Three Gorges dam project (2000–2010) and were provided by Earth Resources Observation Systems (EROS) Data Center. The Three Gorges region receives the majority of its annual precipitation from April to October (Chen, 1993) which is the full growing season for the region (Zhang et al., 2009). One year of MOD13Q1 datasets consist of 23 16-day composite periods. Therefore there are 14 images per year within the active growing season. To maximize the sensitivity of the satellite observation of the impact due to the dam construction, we only consider the annual period of active growth cycle as the vegetation is dormant during the winter.

### *ASTER topographic data and zonation*

ASTER's along-track stereo capability provides topographic data that is used in establishing the elevation zones used for the retrieval of the actual area of vegetation cover in each zone so that the vegetation response at different elevations to reservoir water level change can be calculated. ASTER's DEMs have a spatial resolution of 30 m and vertical accuracy of 15–30 m (LPD USGS EROS Center, 2013). An ASTER DEM image of the Three Gorges Dam region was processed using ArcGIS geoprocessing tools, to delineate the watershed catchment boundaries of the Yangtze River in order to obtain boundaries for the study area (see Fig. 1).

The study area was divided into 6 zones, ranging from the original Yangtze River elevation (66 m) before the dam construction up to the surrounding mountain peaks, each zone spanning 300 m vertically. The first zone covers the nominal inundated area (area submerged by the new reservoir), ranging from the original river elevation of approximately 66 m up to 175 m. From the 175 m contour, 300 m contours were constructed up to the 1375 m mark. All elevations higher than 1375 m were consolidated into a single elevation zone because contours become narrow due to a steepening elevation gradient as elevations increase toward to the maximum elevation of approximately 3000 m.

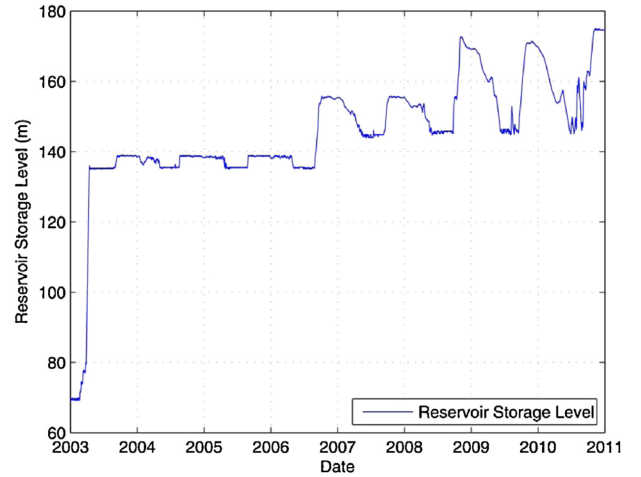


**Fig. 2.** Time series of hourly water level data in the Three Gorges Reservoir for the period 2003–2010. Data were collected by the China Three Gorges Corporation.

**Table 1**
Vegetation cover type classification.

| Vegetation cover type | NDVI classification | EVI classification |
|---|---|---|
| Non-vegetated | NDVI ≤ 0.3 | EVI ≤ 0.2 |
| Sparsely vegetated | 0.3 < NDVI < 0.6 | 0.2 < EVI < 0.3 |
| Densely vegetated | NDVI ≥ 0.6 | EVI ≥ 0.3 |

### *Reservoir storage level data*

Reservoir storage level data collected by China Three Gorges Corporation provided time series information on the changes in water levels as shown in Fig. 2 from January 2003 to December 2010. Collection of the Three Gorges reservoir water level data on an hourly basis started in January 2003, several months before the dam began to impound water. The water level data prior to January 2003 is assumed to not fluctuate outside the original river elevation of 66–75 m (asl) (within the accuracy of the DEM). The Three Gorges Project began impounding water in 2003 up to 139 m. The storage level increased to 156 m in late 2006 and 172.8 m in late 2008. The maximum storage level of 175 m was reached in 2009.

## Data processing strategy

MODIS 16-day 250 m VI images for the growing season (April–October) for the years 2000–2010 were downloaded from a USGS Land Processes Distributed Active Archive Center. Standard MODIS products are organized in a tile system with a sinusoidal projection, and each tile cover an area of 1200 km × 1200 km (approximately 10° latitude × 10° longitude at equator). For simplicity, the land surface is classified into three basic vegetation types according to VI intervals. The first type is non-vegetated land cover that corresponds with NDVI ≤ 0.3 or EVI ≤ 0.2. The second type is sparsely vegetated land cover that corresponds to 0.3 < NDVI < 0.6 or 0.2 < EVI < 0.3. The third type is densely vegetated land cover that corresponds to NDVI ≥ 0.6 or EVI ≥ 0.3 (Bellone et al., 2009; Solano et al., 2010). This classification scheme is shown in Table 1 for convenience of reference. The classification scheme assigns each pixel in each elevation zone to a specific category, depending on the pixel value (VI value).

The data processing includes three basic stages, as shown in Fig. 3. The first stage is preprocessing: zonation of the ASTER DEM image to produce 6 shapefiles, one for each elevation zone and re-projection of all MODIS images from sinusoidal projection to a WGS84, UTM (Zone 49 N) projection system using the MODIS

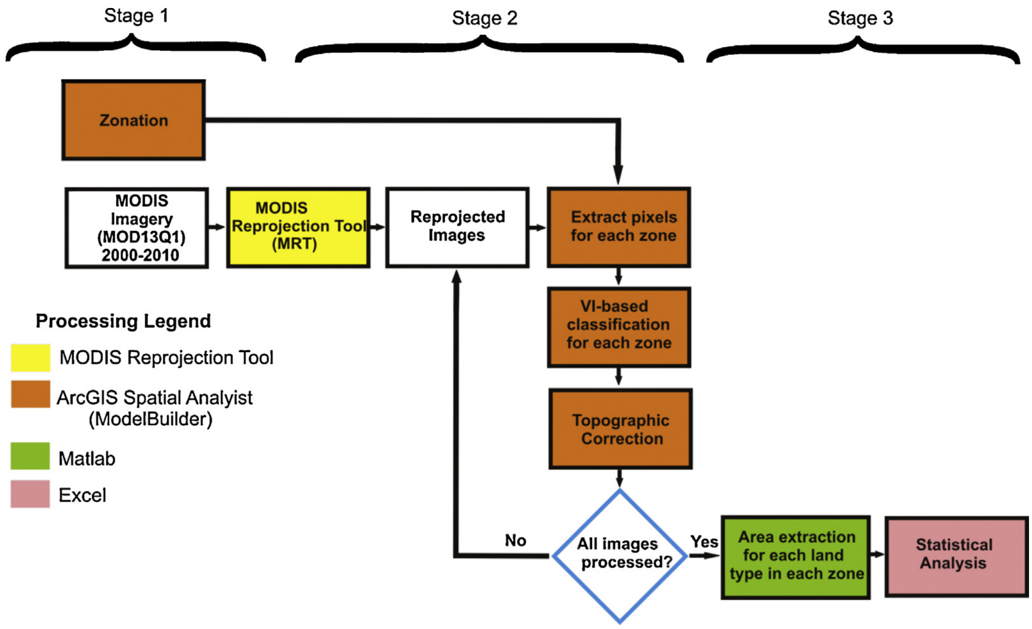


**Fig. 3.** Workflow of the image processing and area derivation for each vegetation type within each elevation zone. Tools used are indicated by different colors. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

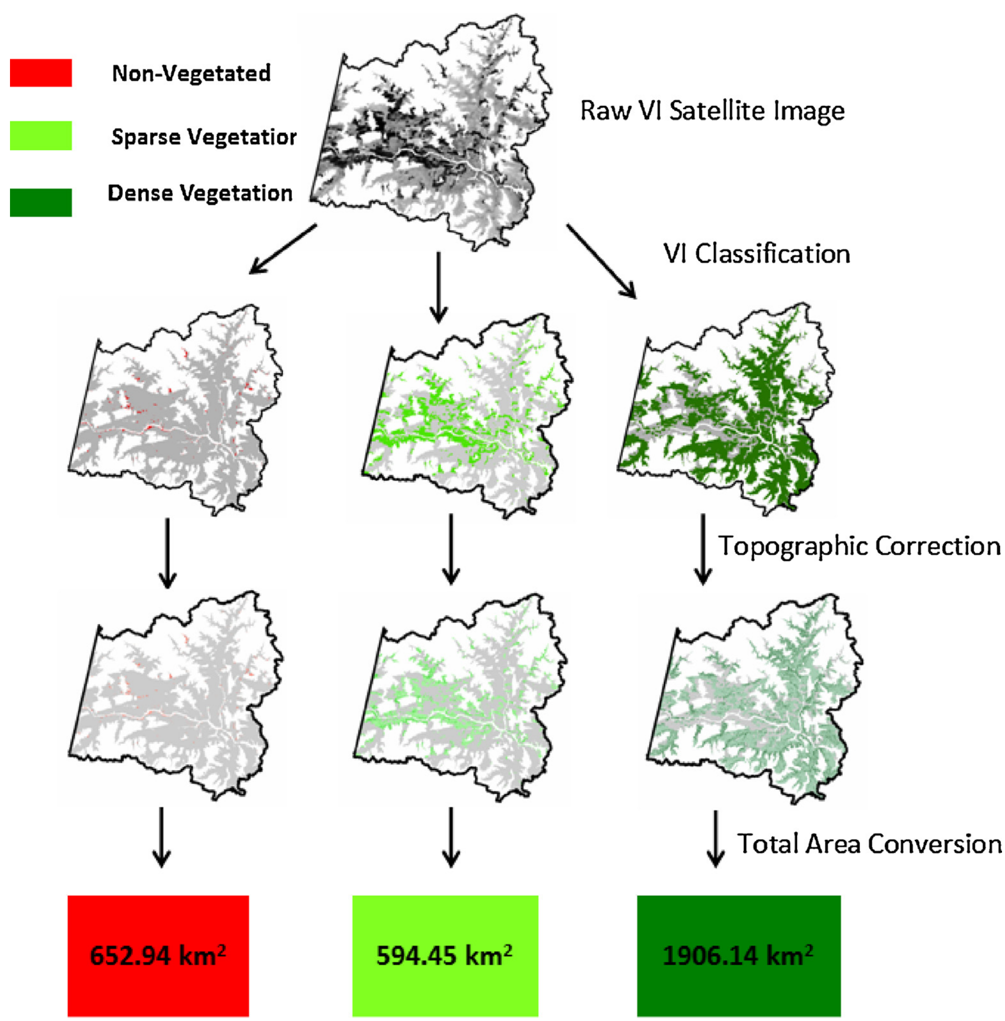


**Fig. 4.** Diagram showing the process of area extraction for each vegetation cover type with a specific elevation zone for a vegetation index (VI) image. Red represents the non-vegetated land cover type. Light green represents the sparsely vegetated type. Dark green represents the densely vegetated type. The raw satellite image used in this example is the June 2010 NDVI image and the elevation zone is Zone 3 (475–775 m). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Reprojection Tool (MRT). MRT is developed by Land Processes Distributed Active Archive Center at USGS Earth Resources Observation and Science (EROS) Center and is used for mosaicking and reprojecting high level MODIS Land products (LPD USGS EROS, 2011). The second stage is an automated processing of all reprojected images to extract the number of pixels and the total surface area that fall into each land type category (Table 1) in each zone using ArcGIS geoprocessing tool (ModelBuilder). Next, all pixels within each elevation zone are extracted from the image, where each pixel value represents the average VI value of any specific area, the area of the pixel represents the actual surface area, and the pixel number of each zone is tracked down. Once all the reprojected images for an entire growing season had been processed, the extracted VI data were run through the classification scheme (see Table 1). The last stage is the post-processing. Once all the data for each elevation zone were categorized, a topographic correction was performed so that each pixel has the actual surface area rather than the nominal area of 250 m × 250 m; the data were imported to a Matlab program and processed through a Category Summation Model, which summarizes each vegetation cover type for each annual growing season. This provides the mean area in each vegetation type for each annual growing season in each elevation zone. The total area (km$^2$) for each vegetation type in each zone was then calculated, providing the total area of each vegetation cover type in each elevation zone. Fig. 4 shows the procedure of the retrieval of the total area for each vegetation type within each elevation zone, taking the June 2010 NDVI image and the elevation Zone 3 (475–775 m) as an example for illustration. A time series of the total area for each vegetation type within each elevation zone was then constructed for the whole construction period (years 2000–2010).

## Results

### *Changes in total vegetation cover with time*

When analyzed solely as a time series, these data can yield subtle details of environmental change. Changes in vegetation resources commonly take place subtly over time and often go undetected and unaddressed without appropriate management actions (Johnson et al., 1976). In order to observe the transformation of NDVI and EVI values and to reveal the areal distribution of each vegetation cover type, the annual time series plots of the total area of each vegetation cover type were constructed for each elevation zone.

Fig. 5 shows the annual series of the total area of non-vegetated land cover type for each zone as derived from NDVI (Fig. 5a) and EVI (Fig. 5b) data. As usual, 95% was taken as the criterion for statistical significance; the results show that there is a consistent increase in the total area of non-vegetated land cover with time in Zones 1–2 ($p < 0.05$) derived from both VI products. These increasing trends for Zones 1–2 indicate a decrease in vegetation for elevations ranging between 66 and 475 m. In Zone 1, the total annual area consistently increases, doubling in area over the 11 year study period. Zone 1 has a total area of 2356.9 km$^2$. The total area of non-vegetated land in Zone 1 increased by 374.8 km$^2$ (or 15.9%) derived from the NDVI product; and it increased by 509.0 km$^2$ (or 21.6%) of the total area of Zone 1 over the study period derived from the EVI product. This zone represents the area which was inundated by the new reservoir water levels. About 134.2 km$^2$ more area of non-vegetated land in Zone 1 was mapped by the EVI product than the NDVI product. Zone 2 (175–475 m), the first 300 m above the maximum water level (75 m), contains a total area of 15,151 km$^2$. In this zone, there is also a consistent increase in loss of vegetation; however, the total area change in this zone is minimal. From 2000 to 2010, the total area of non-vegetated land in Zone 2 increased by 108.6 km$^2$ (or 0.72%) derived from the NDVI product and it increased by 124.1 km$^2$ (or 0.82%) derived from the EVI product. About 15.5 km$^2$ more area of non-vegetated land in Zone 2 was mapped by the EVI product than the NDVI product. Above Zone 2, the annual time series of area was not observed to change significantly over time by both NDVI and EVI products. Both products showed an increase of non-vegetated land in Zones 1–2 and no significant changes in other zones. The EVI product mapped a total of 149.7 km$^2$ more non-vegetated land increase than the NDVI product during the 11 years of dam construction. These results suggest that significant loss in vegetation cover (vegetated to non-vegetated area) during the 11 year span is primarily restricted to the inundated region along with some loss of vegetation cover within the first 300 m above the maximum reservoir level of 175 m.

Fig. 6 shows the annual time series of the total area of sparsely vegetated land cover type for each zone as derived from NDVI (Fig. 6a) and EVI (Fig. 6b) data. A linearly decreasing trend of the area of sparsely vegetative land cover with time was observed significantly for Zones 1–3 ($p < 0.05$) derived from both products. The area of sparsely-vegetated land decreased by 218.7 km$^2$ (or 9.27%) in Zone 1, 1737.8 km$^2$ (or 11.5%) in Zone 2, and 1070.2 km$^2$ (or 4.1%) in Zone 3 as derived from the NDVI product; and it decreased by 198.3 km$^2$ (or 8.4%) in Zone 1, 1730.0 km$^2$ (or 11.4%) in Zone 2, and 2027.6 km$^2$ (or 7.9%) in Zone 3 as derived from the EVI product. The EVI product mapped a total of 929.2.7 km$^2$ more sparsely-vegetated land decrease than the NDVI product during the 11 year of dam construction. Both products showed that the area of sparsely vegetated region decreases with time for area below 775 m in elevation. There is no significant change in area of sparsely vegetated land cover for regions with elevation above 775 m.

Fig. 7 shows the annual time series of the total area of densely vegetated land cover type for each zone derived from NDVI (Fig. 7a) and EVI (Fig. 7b) data. These results show that the total area of densely vegetated land cover in Zone 1 decreases with time: the NDVI product mapped a decrease of 156.1 km$^2$ (or 9.27%) and the EVI product mapped a decrease of 310.7 km$^2$ (or 9.27%). This is consistent with the results shown in Fig. 5 which show an increase in non-vegetated areas. Combined with results in Fig. 5 and Fig. 6 for Zone 1, the results suggest that the original vegetated areas, either sparse or dense, have been inundated. Both products showed an increase in the area of densely-vegetated land cover in Zones 2–3. The area of densely-vegetated land increased by 1629.2 km$^2$ (or 10.8%) in Zone 2 and 1009.2 km$^2$ (or 4.1%) in Zone 3 as derived from the NDVI product; and it increased by 1606.0 km$^2$ (or 10.6%) in Zone 2 and 2150.5 km$^2$ (or 8.4%) in Zone 3 as derived from the EVI product. The EVI product mapped a total of 1118.1 km$^2$ more densely-vegetated land increase than the NDVI product during the 11 year of dam construction. No significant change in the area of densely-vegetated land was observed above Zone 3 or greater than 775 m in elevation. Both products show a consistent linear increase in vegetation cover over time throughout this elevation range (175–775 m) ($p < 0.05$). These trends diminish for region with higher elevation (above Zone 3 or >775 m). This observation is consistent with the results shown in Fig. 6, which indicate that the sparse vegetation decreases in these zones. The area data derived from NDVI show that out of the total area of Zone 2 (15,151 km$^2$), the area of sparsely vegetated land cover decreased by 1737.8 km$^2$ (or 11.5% of the total area of Zone 2) from 2000 to 2010, and area of the non-vegetated land cover increased by 108.6 km$^2$ (or 0.72%), and that of the densely vegetated land cover increased by 1629.2 km$^2$ (or 10.8%) over the study period. Similar results in Zone 2 from EVI data are: the area of the sparsely vegetated land cover decreased by 1730.0 km$^2$ (or 11.4% of the area of Zone 2), the area of the non-vegetated land cover increased by 124.1 km$^2$ (0.82%), and the area of the densely vegetated land cover increased by 1606.0 km$^2$ (or 10.6%) over the study period. For Zone 3,

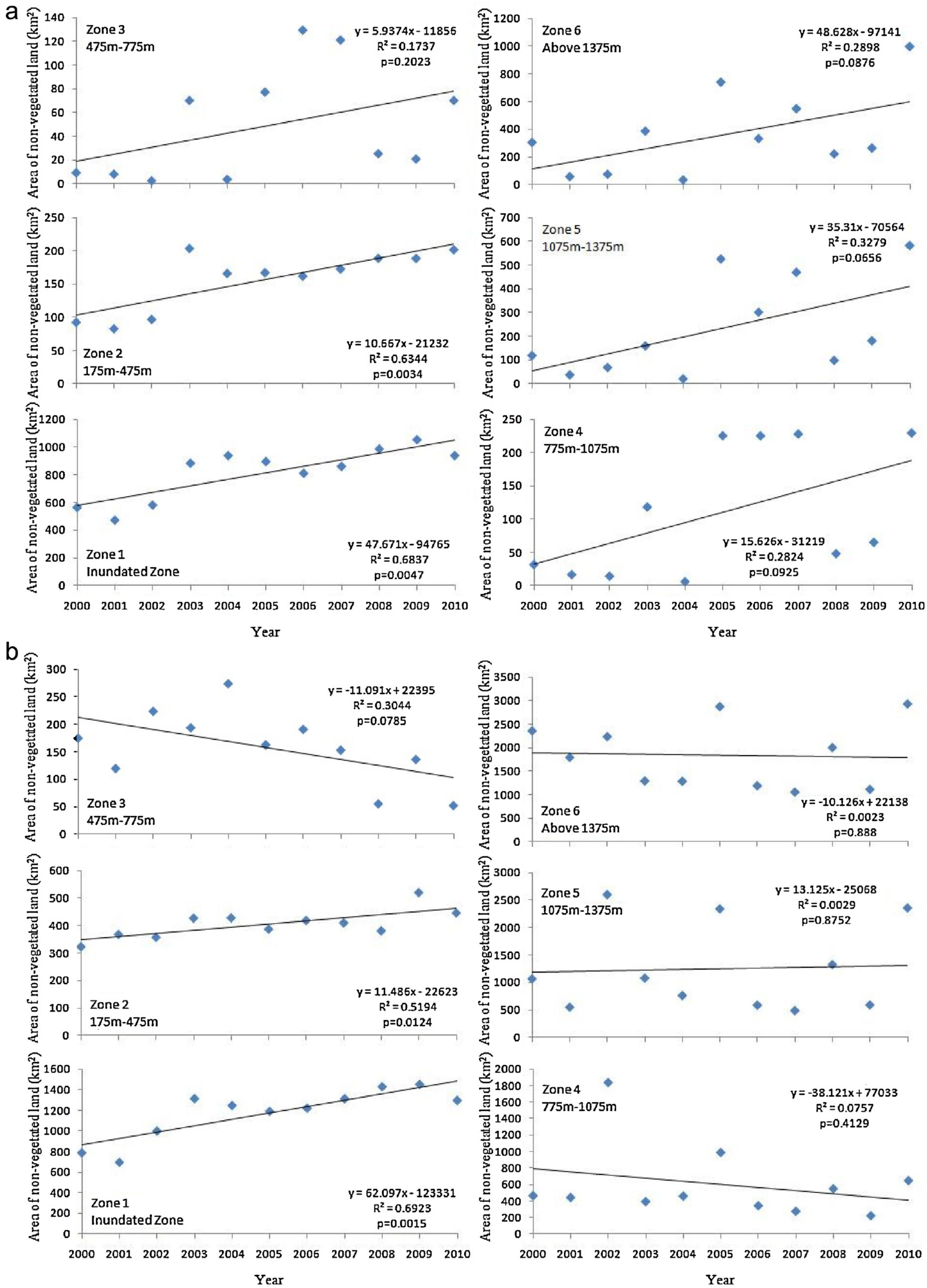


**Fig. 5.** Annual time series of the area of non-vegetated land cover type (NDVI ≤ 0.3 or EVI ≤ 0.2) within each elevation zone for each annual growing season for the years 2000–2010: (a) derived from NDVI data product and (b) derived from EVI data product. Each annual data point is the average of the growing season of the year. Significant trends ($p < 0.05$) were observed only in Zones 1–2 by both products.

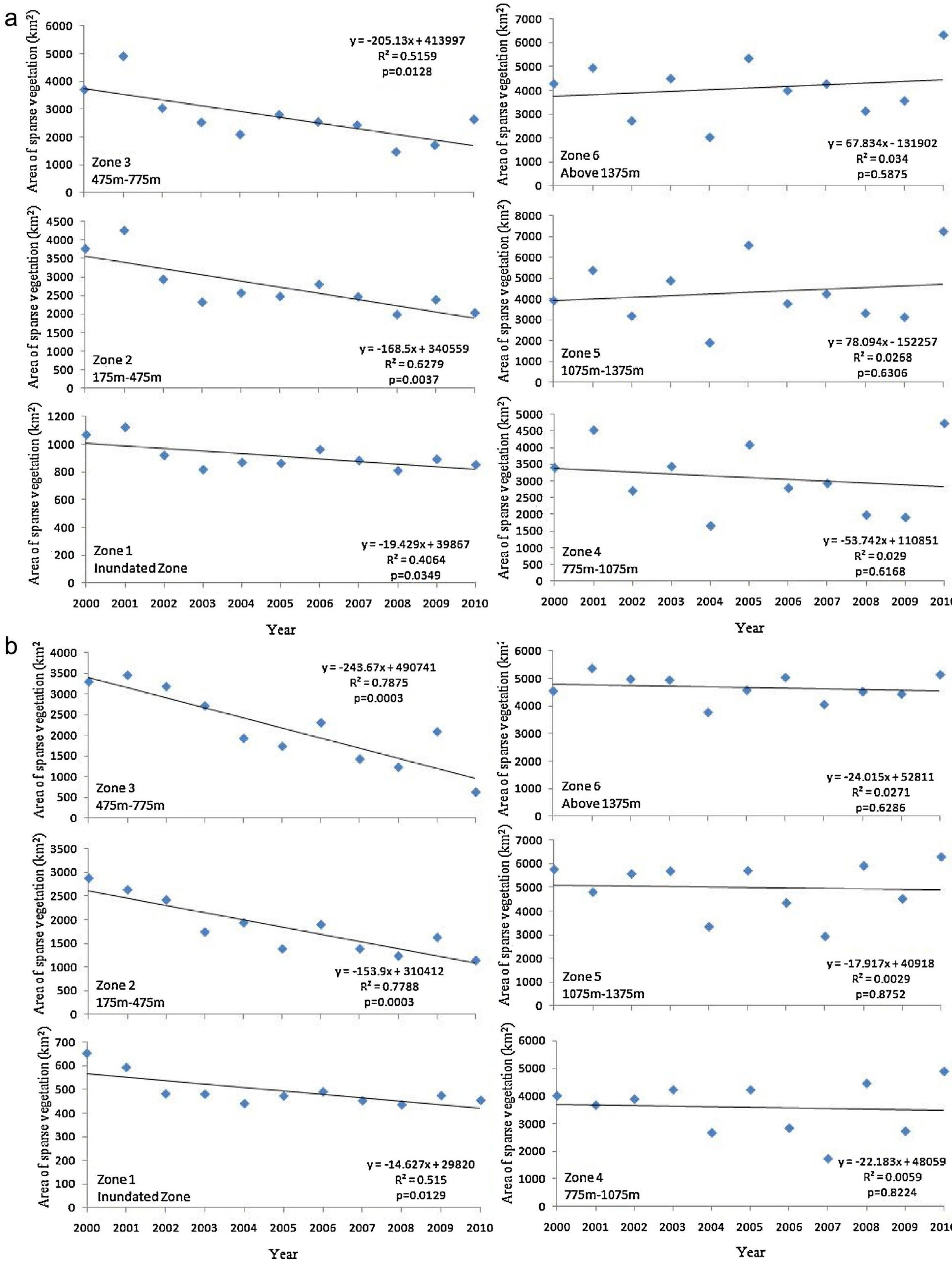


**Fig. 6.** Annual time series of the area of sparsely vegetated land cover type (0.3 < NDVI < 0.6 or 0.2 < EVI < 0.3) within each elevation zone for each annual growing season for the years 2000–2010: (a) derived from NDVI data product and (b) derived from EVI data product. Each annual data point is the average of the growing season of the year. Significant trends ($p < 0.05$) were observed only in Zones 1–3 by both products.

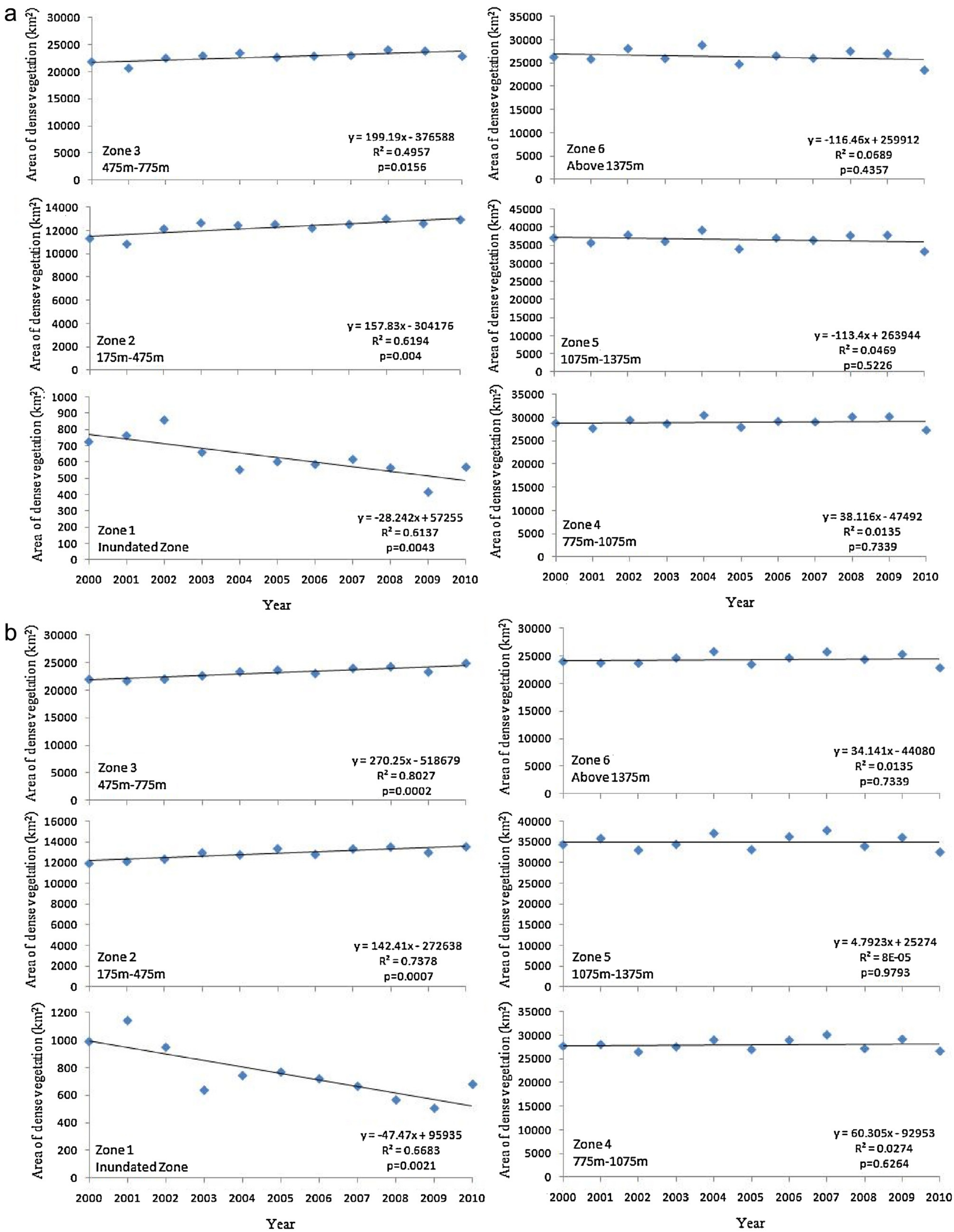


**Fig. 7.** Annual time series of the area of densely vegetated land cover type (NDVI ≥ 0.6 or EVI ≥ 0.3) within each elevation zone for each annual growing season for the years 2000–2010: (a) derived from NDVI data product and (b) derived from EVI data product. Each annual data point is the average of the growing season of the year. Significant trends ($p < 0.05$) were observed only in Zones 1–3 by both products.

non-vegetated land cover was not observed to change significantly from both NDVI and EVI products. The sparsely vegetated land cover decreased by 1070.2 $km^2$ (4.1%) and the densely vegetated land cover increased by 1009.2 $km^2$ (4.1%) from NDVI products from 2000 to 2010. Results from EVI products show that the sparsely vegetated land cover decreased by 2027.6 $km^2$ (7.9%) and the densely vegetated land cover increased by 2150.5 $km^2$ (8.4%) from 2000 to 2010. These results show that in Zone 3 (475–775 m), the sparsely vegetated land cover was converted to densely vegetated land cover. No significant land cover change was observed for any region above 775 m.

Results shown above for the annual time series data of all vegetation canopy types for both NDVI and EVI datasets are summarized in Table 2. The difference in the total area for each vegetation cover type between pre-dam (2000) and post-maximum reservoir storage (2010) for each zone are also shown along with the percentage of these difference values compared to the total area of each zone. During the dam-construction period from 2000 to 2010, area of non-vegetated land cover increased with time in Zones 1–2, especially in Zone 1 (15.9–21.6%); area of sparsely vegetated land cover decreased in Zones 1–3 (66–775 m), while area of densely vegetated area decreased in Zone 1, but increased in Zones 2–3 (175–775 m). This indicates that sparse vegetation progressed into dense vegetation with time. No change in vegetation cover was observed in elevation zones above 775 m.

*Impact of reservoir water level*

To investigate the influence of reservoir water level on the land cover change within each elevation zone, linear regression analysis was performed using the time series of reservoir level data and the time series of the surface area of each vegetation-cover type within each elevation zone. To this end, both data sets had to be of the same temporal resolution. Therefore, the hourly reservoir water level data collected by the China Three Gorges Corporation (Fig. 2) were averaged to obtain the 16-day and annual averages for each annual growing season (April to October). The average water level elevation prior to 2003 was about 66 m, the original elevation of the Yangtze River prior to the dam construction (Ponseti and López-Pujol, 2006). The average reservoir level during the growing season of each year was correlated to the total area of each vegetation cover type. These correlations were performed in order to investigate how each step-up in reservoir level during the construction period impact the area changes of each land cover type within each elevation zone. From these correlations, the elevation zones mostly affected by the changes in reservoir storage level in terms of area change of each vegetation cover type can be determined.

Fig. 8 shows the annual total area of non-vegetated land type for each zone versus the reservoir water level for both NDVI (Fig. 8a) and EVI (Fig. 8b) data products. The results show that the correlation between the area of non-vegetated land cover with reservoir water level is significant ($p < 0.05$) for Zones 1–2 (66–475 m in elevation), but not significant in Zones 3–6 (elevation > 475 m). The correlation between the total area of the non-vegetated land cover and the reservoir water level has lower correlation coefficient for EVI than NDVI products in Zones 1–2 ($R = 0.913$ for EVI versus 0.946 for NDVI in Zone 1; 0.730 for EVI versus 0.926 for NDVI in Zone 2). NDVI seems to be more sensitive to mapping non-vegetated land cover change due to the reservoir water level change. These results suggest that changes in non-vegetated land cover in Zones 1–2 are related to the rising water levels of the newly formed reservoir. As is expected, area of non-vegetated land cover, basically inundated area in Zone 1 does show a strong correlation with the reservoir level due to the complete inundation of this zone by the end of the study period in 2010.

Fig. 9 shows the annual total area of sparsely vegetated land type for each zone versus the reservoir water level derived from both NDVI (Fig. 9a) and EVI (Fig. 9b) data products. The correlation between the total area of the sparsely-vegetated land cover and the reservoir water level has higher correlation coefficient (absolute value) for EVI than NDVI products in Zones 1–3 ($R = -0.780$ for EVI versus −0.750 for NDVI in Zone 1, −0.921 for EVI versus −0.852 for NDVI in Zone 2, and −0.887 for EVI versus −0.803 for NDVI in Zone 3). EVI seems to be more sensitive to mapping sparsely-vegetated land cover change due to reservoir water level change. The correlation is not significant for Zones 4–6. The above results indicate that the area of sparsely vegetated land cover derived from both products decreases with increasing reservoir water level within Zones 1–3 (inundation zone – 775 m). However, for region with elevation greater than 775 m (Zones 4–6), the correlation is not significant ($p > 0.05$), indicating the impact of reservoir water level on the sparsely vegetated land is minimum at these higher elevations.

Fig. 10 shows the annual total area of the densely vegetated cover type for each elevation zone versus reservoir water level derived from NDVI (Fig. 10a) and EVI (Fig. 10b) data products. The correlation between the total area of the densely-vegetated land cover and the reservoir water level has higher correlation coefficient (absolute value) for EVI than NDVI products in Zones 1–3 ($R = -0.900$ for EVI versus −0.879 for NDVI in Zone 1, 0.898 for EVI versus 0.842 for NDVI in Zone 2, and 0.893 for EVI versus 0.784 for NDVI in Zone 3). EVI seems to be also more sensitive to mapping densely-vegetated land cover change due to the reservoir water level change. The correlation is significant ($p < 0.05$) in Zones 1–3, but not in Zones 4–6 for both NDVI and EVI products. Both products show that the area of dense vegetation decreases with increasing water level because of inundation. For Zones 2–3 (175–775 m), the area of dense vegetation increases with increasing water level in each zone. This suggests that the size of the area of densely vegetated land cover in these zones is positively influenced by the rising water levels of the reservoir. These results are consistent with those derived from Fig. 9 and may suggest that some areas of sparse vegetation progressed into areas of more dense vegetation. However, for regions with elevations greater than 775 m (Zones 4–6), the correlation is not significant ($p > 0.05$), indicating that the impact of reservoir water level on the densely vegetated land is minimum. Fig. 11 shows two photos taken on June 8, 2011, showing the maximum water level line and the distribution of shrub above the inundation zone (Zone 1). Area between the maximum water level line (175 m) and the original water level 66 m before dam construction was either water or almost bare land because of inundation.

Results discussed above for the annual time series data of all land cover types versus reservoir water level for both NDVI and EVI datasets are summarized in Table 3. With increasing reservoir water level, area of non-vegetated land cover increased in Zones 1–2 (elevation 66–475 m), area of the sparsely-vegetated land cover decreased in Zones 1–3 (elevation 66–775 m), area of the densely-vegetated land cover decreased in Zone 1 (66–175 m) but increased in Zones 2–3 (175–775 m). Land cover change due to increasing reservoir water level was not observed in elevation zones above 775 m. Increasing water level inundated both sparely and densely-vegetated areas in the inundation zone (Zone 1, 66–175 m). Increasing reservoir water level indirectly caused the progression of sparse vegetation into dense vegetation in Zones 2–3 (175–775 m). Fig. 12 shows the summary of results, illustrating the riparian elevation zones most affected and not impacted by rising reservoir storage levels from 2000 to 2010. Zone 1 in red is the inundated zone (below 175 m), directly impacted by the water level. Area in green within Zones 2–3 (175 to 775 m) shows an overall increase in vegetation cover overtime. Area in gray represents elevations above 775 m, showing no impact.

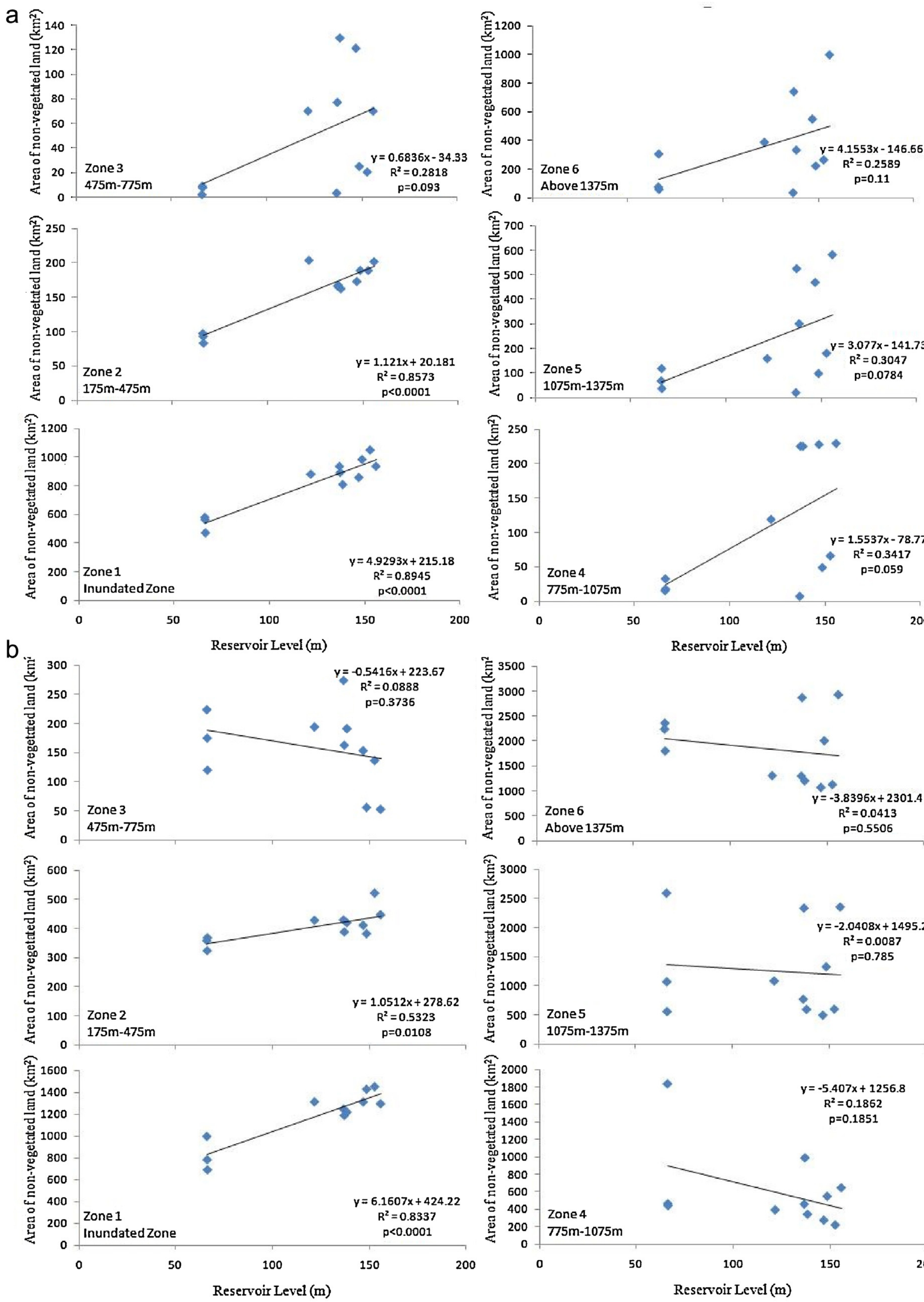


**Fig. 8.** The annual total area of the non-vegetated land type for each zone versus the reservoir water level time series data: (a) derived from NDVI data product and (b) derived from EVI data product. Significant correlations ($p < 0.05$) were observed only in Zones 1–2 by both products.

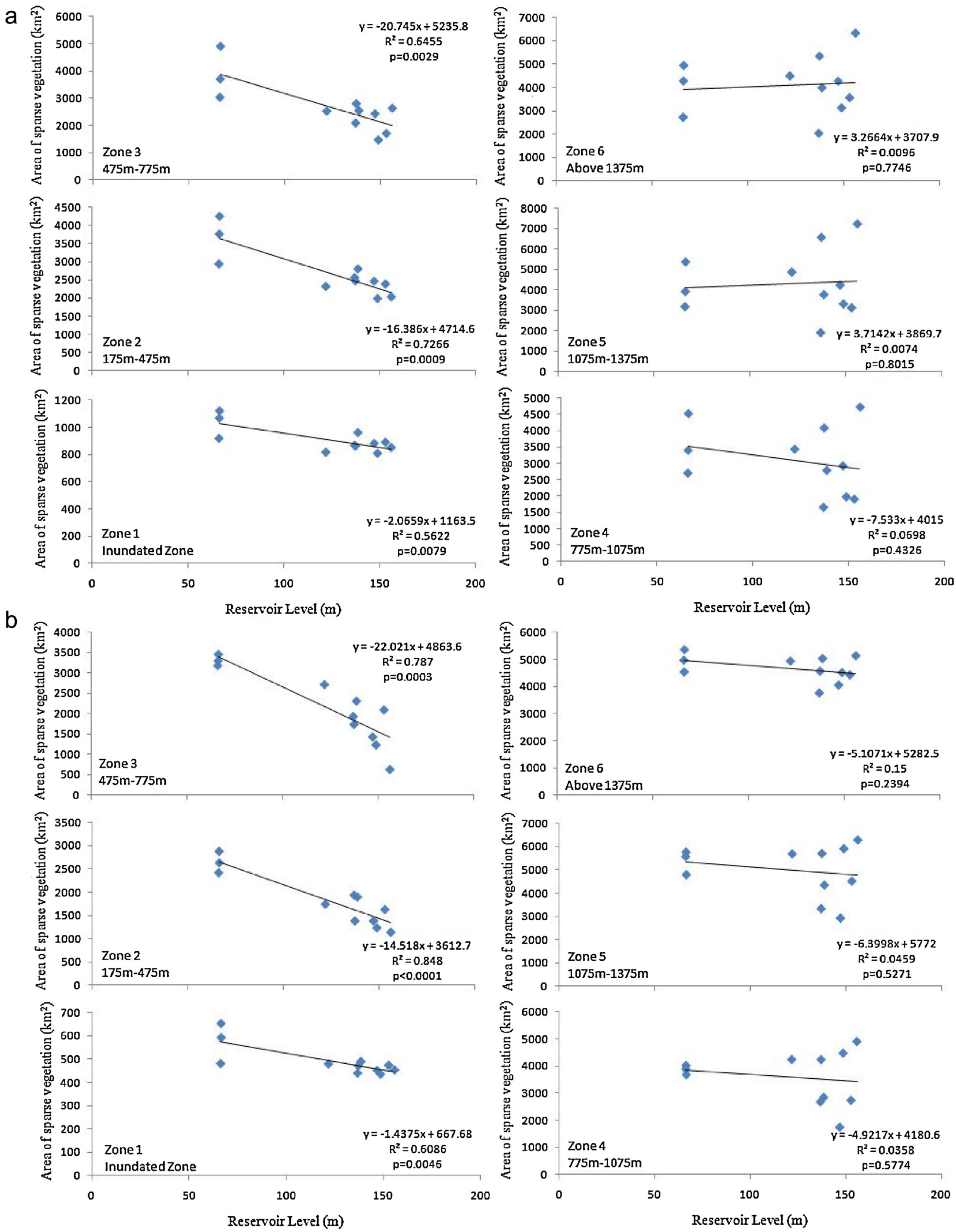


**Fig. 9.** The annual total area of the sparsely vegetated land type for each zone versus the reservoir water level time series data: (a) derived from NDVI data product and (b) derived from EVI data product. Each annual data point is the average of the growing season of the year. Significant correlations ($p < 0.05$) were observed only in Zones 1–3 by both products.

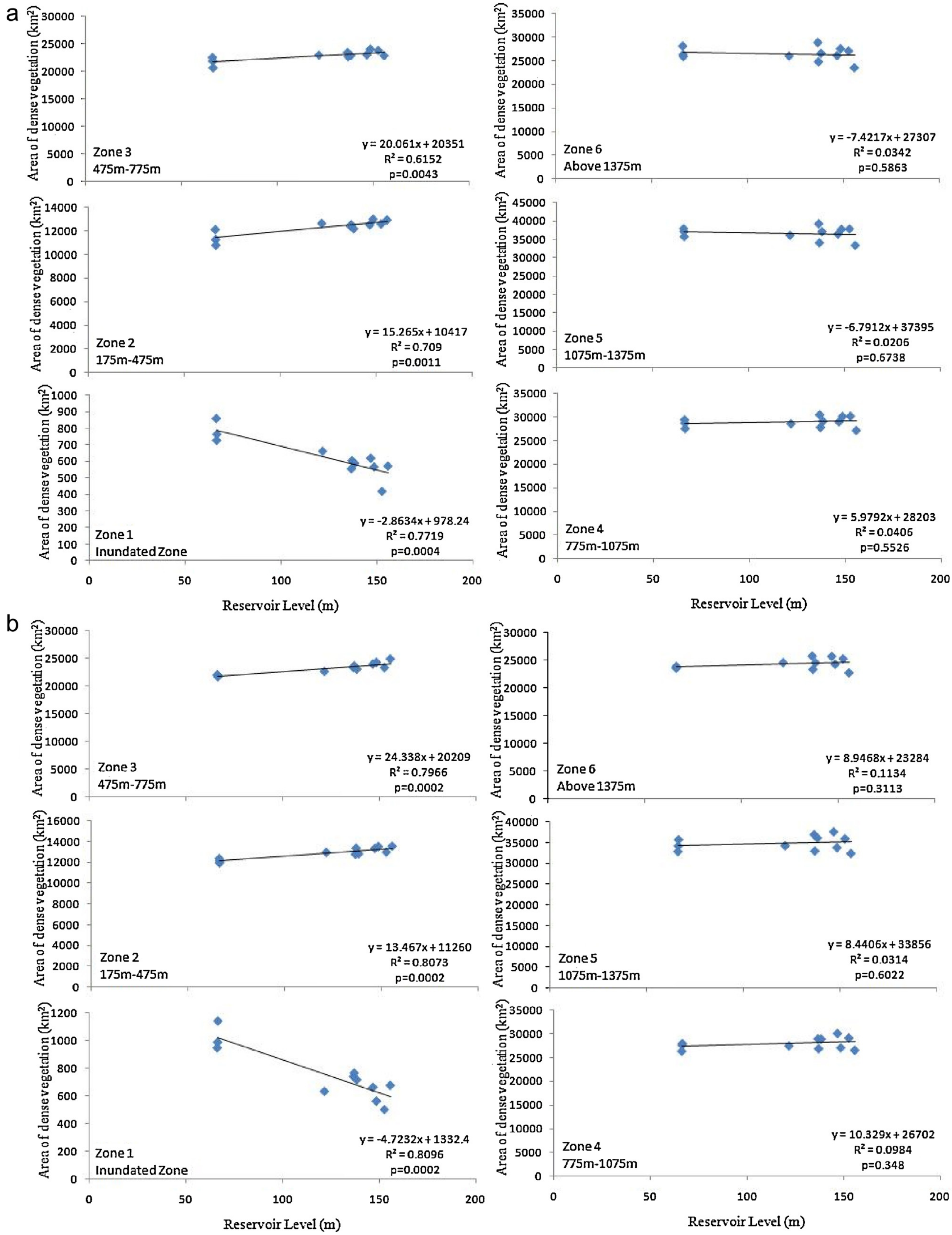


**Fig. 10.** The annual total area of the densely vegetated land type for each zone versus the reservoir water level time series data: (a) derived from NDVI data product and (b) derived from EVI data product. Significant correlations ($p < 0.05$) were observed only in Zones 1–3 by both products.


(a) (b)

**Fig. 11.** (a) Photo shows the maximum water level line. Area between 175 m and the original water level 66 m before dam was either water or almost bare land. (b) Photo shows the dense shrub above the inundation zone (Zone 1). Both photos were taken on June 8, 2011.

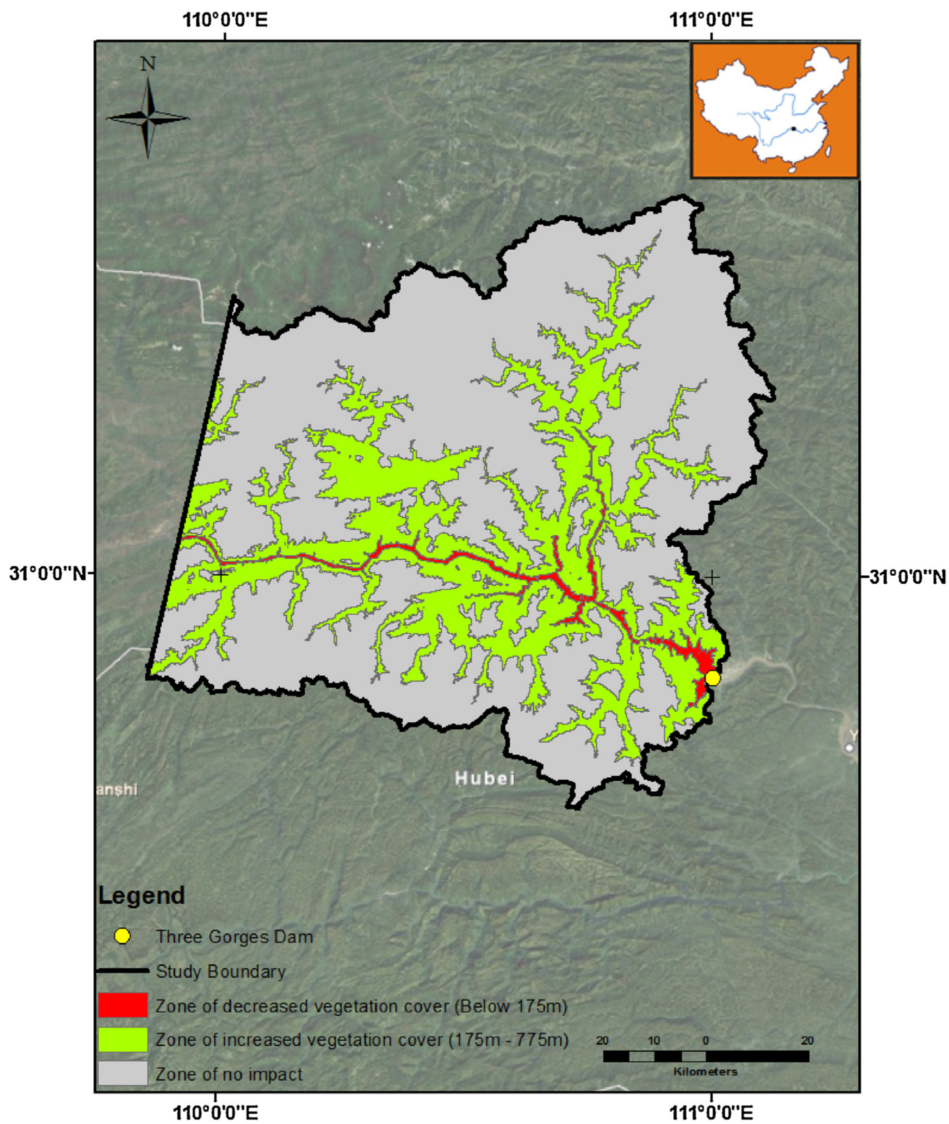


**Fig. 12.** Summary of results, illustrating regions most affected by rising reservoir storage water levels from 2000 to 2010. Red represents the inundated zone (below 175 m). Green represents elevations showing an overall increase in vegetation cover over time (175–775 m). Gray represents elevations showing no impact in vegetation cover (above 775 m). The location of the Three Gorges Dam is represented by a yellow dot. Black square on the outlined map of China indicates the location of the study site. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

**Table 2**
Summary of results of annual time series of area of each vegetation cover type in each elevation zone derived from NDVI and EVI data products. Units: ($km^2$; %).

| Zone | NDVI-based | | | EVI-based | | |
|---|---|---|---|---|---|---|
| | Non-vegetated | Sparsely vegetated | Densely vegetated | Non-vegetated | Sparsely vegetated | Densely vegetated |
| 1 | ↑ (+374.8; 15.9%) | ↓ (−218.7; 9.27%) | ↓ (−156.1; 6.6%) | ↑ (+509.0; 21.6%) | ↓ (−198.3; 8.4%) | ↓ (−310.7; 13.2%) |
| 2 | ↑ (+108.6; 0.72%) | ↓ (−1737.8; 11.5%) | ↑ (+1629.2; 10.8%) | ↑ (+124.1; 0.82%) | ↓ (−1730.0; 11.4%) | ↑ (+1606.0; 10.6%) |
| 3 | ~ | ↓ (−1070.2; 4.1%) | ↑ (+1009.2; 4.1%) | ~ | ↓ (−2027.6; 7.9%) | ↑ (+2150.5; 8.4%) |
| 4 | ~ | ~ | ~ | ~ | ~ | ~ |
| 5 | ~ | ~ | ~ | ~ | ~ | ~ |
| 6 | ~ | ~ | ~ | ~ | ~ | ~ |

*Note*: ↑ (↓) indicates the area of the vegetation type increases (decreases) in the zone; (~) indicates no significant relationship was observed. The first number in the parentheses is the area change between pre-dam (2000) and post-maximum reservoir level (2010), either increase (+) or decrease (−), and the second number in % is the percentage of the change of the total area of each zone.

**Table 3**
Summary of area change of each vegetation type in each zone derived from the NDVI and EVI data products as water levels increase.

| Zone | NDVI-based | | | EVI-based | | |
|---|---|---|---|---|---|---|
| | Non-vegetated | Sparsely vegetated | Densely vegetated | Non-vegetated | Sparsely vegetated | Densely vegetated |
| 1 | ↑ | ↓ | ↓ | ↑ | ↓ | ↓ |
| 2 | ↑ | ↓ | ↑ | ↑ | ↓ | ↑ |
| 3 | ~ | ↓ | ↑ | ~ | ↓ | ↑ |
| 4 | ~ | ~ | ~ | ~ | ~ | ~ |
| 5 | ~ | ~ | ~ | ~ | ~ | ~ |
| 6 | ~ | ~ | ~ | ~ | ~ | ~ |

*Note*: ↑ (↓) indicates the area of the vegetation type increases (decreases) in the zone; (~) indicates no significant relationship was observed.

## Discussion and conclusions

Changes in land cover in the Three Gorges region have been the focus of multiple previous studies (Jabbar et al., 2006; Zeng et al., 2008; Zhang et al., 2009; Gao and Mao, 2009; Seeber et al., 2010). However, the impact of the dam construction and the huge amount of impounded water above the dam on vegetation cover change at different elevation zones has not been investigated before. This research focused on the impact on vegetation cover at different elevation zones due to dam construction using MODIS 250 m VI (NDVI and EVI) data and the upstream of the recently constructed Three Gorges Dam site. One of the initial, most obvious and certain environmental impacts of the dam is the loss of vegetation through inundation (New and Xie, 2008), but this study shows that the loss of vegetation seems to be limited to the inundation zone from elevation 66 to 175 m, the maximum water level. The Three Gorges Dam began impounding water in 2003 and the maximum reservoir level of 175 m was reached in 2009. Results derived from NDVI and EVI products using ArcGIS techniques did show that there has been a significant loss of vegetated area in Zone 1 (66–175 m) due to inundation by water.

Regression analysis of the area of densely vegetated land cover derived from NDVI and EVI data products with the reservoir levels indicates that there is a general increase in densely vegetated cover in the elevation Zones 2–3 (175–775 m) over the time period of this study. This increase may be due to an increase in moisture in the atmosphere and subsequent precipitation within these elevation zones caused by the lake effect. The presence of a new body of standing water due to the dam construction and impoundment of water changed the hydrological regime by enhanced evaporation and an increase in atmospheric moisture in the vicinity of the reservoir. The total amount of evaporation is proportional to the size of the water body. Lake effect precipitation plays an important role in the weather and hydrology of many regions near the shores of large bodies of water (Lofgren, 2006). Enhanced evaporation can result in changes in the annual precipitation patterns and an increase in low stratus clouds and fog (Baxter, 1977). The Three Gorges region is very mountainous. The lake effect can be enhanced when the moving air mass is uplifted by the orographic influence of higher elevations (topographic forcing of air upward as it reaches the shoreline). In the investigation of a precipitation simulation model, Lofgren (2006) found a reduction in surface roughness (topographic relief) causes a reduction in the lake effect precipitation in the immediate vicinity of the lake and which is consequently spread over a larger area. Hjelmfelt (1990) investigated the effects of including versus excluding orography and found that orography enhances lake effect precipitation. This indicates the potential for lake effect microclimates to establish zones of localized zones of precipitation in mountainous regions. This could potentially explain why the vegetation cover increase in Zones 2–3 (175–775 m), as observed in this study.

However, no significant area change of any land cover (non-vegetated, sparsely vegetated, and densely vegetated) in the region above 775 m was observed either with time or with reservoir water level. This observation agrees with that by Jiang et al. (2005) that little change in vegetation cover is observed at higher elevations. This may indicate that the hydro-meteorological processes of evaporation and condensation are limited to a certain elevation (≤775 m) due to the barrier of higher mountain.

Continued investigation is needed in order to determine the exact cause of these changes in vegetation cover. The response of vegetation to raising water level change is likely not instantaneous and the potential exists for a prolonged delay of response, making it likely that the ultimate consequences of the sudden increase in water levels are not yet fully manifested within the ecosystem. In the short term, research being carried out in the Three Gorges region will provide some insight in this area, but given the long-term nature of the responses of habitats, it will not be until 30 or more years in the future that the full impacts of the dam will become evident. With the resettlement of over 1.2 million people throughout the Three Gorges region, active management, monitoring, and restoration programs are needed to maintain the habitat value of this ecosystem for the future. Sustainable development of the Three Gorges Reservoir area is crucial to the long term benefits of millions of people.

In summary, an investigation on the long term impact of the Three Gorges Dam construction and the impounded water on the riparian vegetation cover change upstream the dam was performed by integrating remote sensing with ArcGIS techniques. Results show that over the dam construction period (2000–2010), using MODIS vegetation indices (NDVI and EVI) products, digital elevation model (DEM) data from ASTER, and the time series water level data of the Three Gorges reservoir as the data source, non-vegetated land cover increased in the inundated zone (below 175 m); dense vegetation land cover increased within the elevation zones between 175 and 775 m and no change in vegetation cover was observed above 775 m in elevation. Increasing water levels have had a negative impact on vegetation cover below 175 m; a positive impact on vegetation cover is limited to the region between 175 and 775 m and no significant correlation was observed above 775 m. Results also suggested that MODIS EVI product is less sensitive in mapping non-vegetated land cover change, but more sensitive in mapping vegetated land cover change, caused by the reservoir water level variation; both products are similar in effectively tracking a trend between land cover change in each elevation zone with time or with reservoir water level.

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## References

Baxter, R.M., 1977. Environmental effects of dams and impoundments. Annu. Rev. Ecol. Syst. 8, 255–283.
Beck, P., Atzberger, C., Hogda, K., Johansen, B., Skidmore, A., 2006. Improved monitoring of vegetation dynamics of very high latitudes: a new method using MODIS NDVI. Remote Sens. Environ. 100, 321–334.
Bellone, T., Boccardo, P., Perez, F., 2009. Investigation of vegetation dynamics using long-term normalized difference vegetation index time series. Am. J. Environ. Sci. 5 (4), 460–466.
Chen, G., 1993. Studies on Influences of Three Gorges Project on Ecological Environment. Science Press, Beijing, China.
Chen, Z., Wang, J., 2010. Land use and land cover change detection using satellite remote sensing techniques in the mountainous Three Gorges area, China. Int. J. Remote Sens. 31 (60), 1519–1542.
DOE (U.S. Department of Energy), 2004. Hydropower: Setting a course for our energy future. Available online at: http://www.nrel.gov/docs/fy04osti/34916.pdf
Fu, B., Wu, B., Lü, Y., Xu, Z., Cao, J., Niu, D., Yang, G., Zhou, Y., 2010. Three Gorges Project: efforts and challenges for the environment. Prog. Phys. Geog. 34 (6), 741–754.
Fuggle, R., Smith, W.T., Hydrosult Canada Inc., Agrodev Canada Inc., 2000. Large dams in water and energy resource development in The People's Republic of China (PRC). A country review paper prepared as an input to the World Commission on Dams, Cape Town.
Gao, X., Huete, A.R., Ni, W., Miura, T., 2000. Optical–biophysical relationships of vegetation spectra without background contamination. Remote Sens. Environ. 74 (3), 609–620.
Gao, Q., Mao, H., 2009. Ecological restoration, social-economic changes and sustainable development in the Three Gorges Reservoir area: a case study in Yunyang, Chongqing Municipality. Int. J. Sust. Dev. World Ecol. 14, 174–181.
Hansen, M.C., Defries, R.S., Townshend, J.R.G., Sohlberg, R., Dimiceli, C., Carroll, M., 2002. Towards an operational MODIS continuous field of percent tree cover algorithm: examples using AVHRR and MODIS data. Remote Sens. Environ. 83, 303–319.
Hayashi, S., Murakami, S., Xu, K., Watanabe, M., 2008. Effects of the Three Gorges Dam Project on flood control in the Dongting Lake area, China, in a 1998-type flood. J. Hydro-environ. Res. 2, 148–163.
Hayes, D.J., Cohen, W.B., 2007. Spatial, spectral and temporal patterns of tropical forest cover change as observed with multiple scales of optical satellite data. Remote Sens. Environ. 106 (1), 1–16.
Hayes, D.J., Cohen, W.B., Sader, S.A., Irwin, D.E., 2008. Estimating proportional change in forest cover as a continuous variable from multi-year MODIC data. Remote Sens. Environ. 112, 735–749.
He, L., King, L., Jiang, T., 2003. On the land use in Three Gorges Reservoir area. J. Geogr. Sci. 13 (4), 416–422.
Hjelmfelt, M.R., 1990. Numerical study of the influence of environmental conditions on lake-effect snowstorms over Lake Michigan. Mon. Weather Rev. 118 (1), 138–150.
Huete, A.R., Didan, K., Miura, T., Rodreguez, E., 2002. Overview of the radiometric and biophysical performance of the MODIS vegetation indices. Remote Sens. Environ. 83, 195–213.
Huete, A.R., Liu, H., 1994. An error and sensitivity analysis of the atmospheric- and soil-correcting variants of the NDVI for the MODIS-EOS. IEEE Trans. Geosci. Remote Sens. 32, 897–905.
Huete, A.R., Liu, H., Batchily, K., Van Leeuwen, W., 1997. A comparison of vegetation indices global set of TM images for EOS-MODIS. Remote Sens. Environ. 59, 440–451.
International Hydropower Association, 2000. Hydropower and the world's energy future. November, 2000. Available online at: http://ieahydro.org/reports/Hydrofut.pdf
Jabbar, M., Shi, Z., Wang, T., Cai, C., 2006. Vegetation change prediction with geo-information techniques in the Three Gorges area of China. Pedosphere 16 (4), 457–467.
Jiang, M., Deng, H., Cai, Q., Wu, G., 2005. Species richness in a riparian plant community along the banks of the Xiangxi River, the Three Gorges region. Int. J. Sust. Dev. World Ecol. 12 (1), 60–67.
Johnson, W.C., Burgess, R.L., Keammerer, W.R., 1976. Forest overstory vegetation and environment on the Missouri River floodplain in North Dakota. Ecol. Monogr. 46, 59–84.
Justice, C.O., Townshend, J.R.G., Vermote, E.F., Masuoka, E., Wolfe, R.E., Saleous, N., 2002. An overview of MODIS land data processing and product status. Remote Sens. Environ. 83 (1–2), 3–15.
Liu, S., Chen, Z., Chen, G., 2004. Impact of urbanization and resettlement on employment of rural inhabitants in China – a case study in Changling Town, Chongqing Municipality, Three Gorges Reservoir Area. Mt. Res. Dev. 24, 228–233.
Lofgren, B., 2006. Land surface roughness effects on lake effect precipitation. J. Great Lakes Res. 32, 839–851.
LPD USGS EROS Center, 2013. Digital elevation model & registered radiance at the sensor – orthorectified. Available online at: https://lpdaac.usgs.gov/products/aster_products_table
LPD USGS EROS, 2011. MODIS reprojection tool user's manual, Release 4.1, April 2011, pp. 1–69. Available online at: https://lpdaac.usgs.gov/sites/default/files/public/mrt41_usermanual_032811.pdf
New, T., Xie, Z., 2008. Three Gorges Project: impact of large dams on riparian vegetation: applying global experience to the case of China's Three Gorges Dam. Biodivers. Conserv. 17, 3149–3163.
Ponseti, M., López-Pujol, J., 2006. The Three Gorges Dam project in China: history and consequences. ORIENTATS-2006, ISSN 1696-4403.
Railsback, S.F., Cada, G.F., Petrich, C.H., Sale, M.J., Shaakir-Aii, J.A., Watts, J.A., Webb, J.W., 1991. Environmental impacts of increased hydroelectric development at existing dams. Oak Ridge National Laboratory, ORNL/TM-11673, pp. 1–46.
Rouse, J.W., 1973. Monitoring the vernal advancement and retrogradation of natural vegetation. NASA/GSFCT Type II Report. NASA, Greenbelt, MD.
Sahin, S., Kurum, E., 2002. Erosion risk analysis by GIS in environmental impact assessment: a case study – SeyhanKopru Dam construction. J. Environ. Manage. 66 (3), 239–247.
Seeber, C., Hartmann, H., Wei, X., King, L., 2010. Land use change and causes in the Xiangxi catchment, Three Gorges area derived from mulitispectral data. J. Earth Sci. 21 (6), 846–855.
Sivanpillai, R., Latchininsky, A.V., Driese, K.L., Kambulin, V.E., 2006. Mapping locust habitats in River Ili Delta, Kazakhstan, using Landsat imagery. Agric. Ecosyst. Environ. 117 (2–3), 128–134.
Solano, R., Didan, K., Jacobson, A., Huete, A., 2010. MODIS vegetation index user's guide (MOD13 series), Version 2.00 (Collection 5). Available online at: http://vip.arizona.edu/documents/MODIS/MODIS_VI_UsersGuide_01_2012.pdf
Subklew, G., Ulirch, J., Furst, L., Holtkemeier, A., 2010. Environmental impacts of the Yangtze Three Gorges project: an overview of the Chinese-German research cooperation. J. Earth Sci. 21 (6), 817–823.
Sun, Z., Ma, R., Wang, Y., 2009. Using Landsat data to determine land use changes in Datong basin, China. Environ. Geol. 57, 1825–1837.
Townshend, J.R.G., Justice, C.O., 1988. Selecting the spatial resolution of satellite sensors required for global monitoring of land transformations. Int. J. Remote Sens. 9, 187–236.
Tullos, D., 2009. Assessing the influence of environmental impact assessment on science and policy: an analysis of the Three Gorges Project. J. Environ. Manage. 90, 208–223.
Wang, Z., 2002. Three Gorges project. Public Admin. Dev. 22, 369–375.
Wardlow, B.D., Egbert, S.L., Kastens, J.H., 2007. Analysis of time-series MODIS 250 m vegetation index data for crop classification in the U.S. central Great Plains. Remote Sens. Environ. 108, 290–310.
Wessels, K.J., Defries, R.S., Dempewolf, J., Anderson, L.O., Hansen, A.J., Powell, S.L., 2004. Mapping regional land cover with MODIS data for biological conservation: examples from the Great Yellowstone Ecosystem, USA and Para State, Brazil. Remote Sens. Environ. 92, 67–83.
Wu, L., Zhang, Q., Zhihong, J., 2006. Three Gorges Dam affects regional precipitation. Geophys. Res. Lett. 33, 1–4.
Zeng, Y., Schaepman, M.E., Wu, B., Clevers, J., Bregt, A., 2008. Scaling-based forest structural change detection using an inverted geometric-optical model in the Three Gorges region of China. Remote Sens. Environ. 112 (1), 4261–4271.
Zhang, J., Liu, Z., Sun, X., 2009. Changing landscape in the Three Gorges Reservoir area of Yangtze River from 1977 to 2005: land use/land cover, vegetation cover changes estimated using multi-source satellite data. Int. J. Appl. Earth Obs. Geoinform. 11 (6), 403–412.
Zhou, X., Guan, H., Xie, H., Wilson, J.L., 2009. Analysis and optimization of NDVI definitions and areal fraction models in remote sensing of vegetation. Int. J. Remote Sens. 30 (3), 721–751.