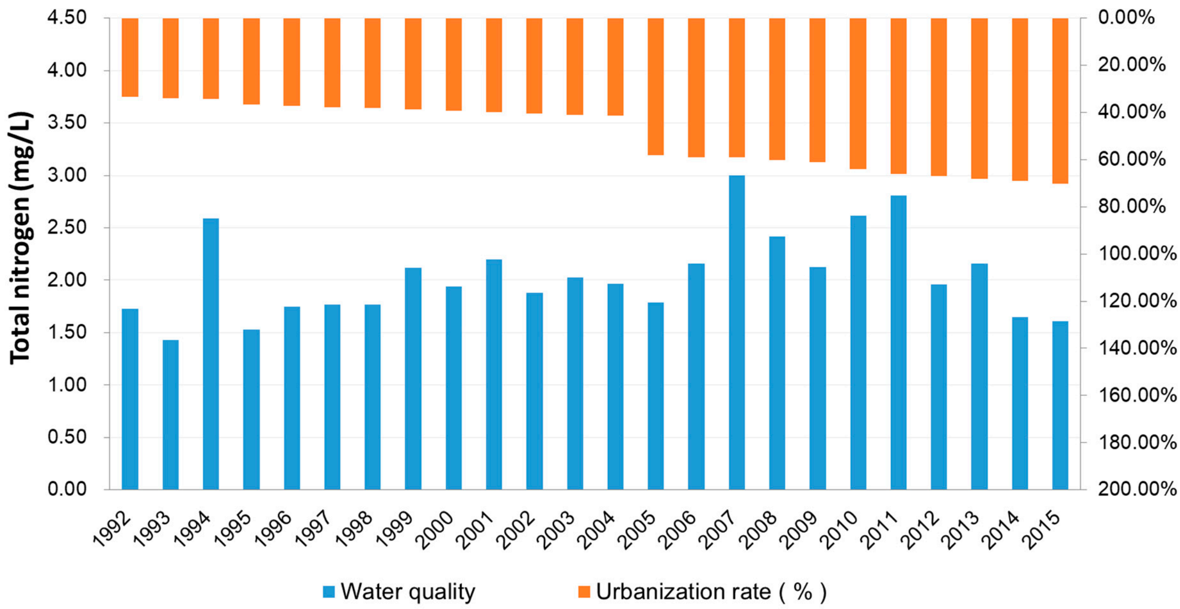


**Figure S1.** Changes in urbanization rate and water quality (represented by total nitrogen content) in Dianchi Lake Basin, 1992–2015.

**Table S1.** Results of power regression analysis of built-up area (dependent variable) and potential influencing factors (independent variable).

| Figure 0 | Indicator | Explanation | Regression Coefficient * |
|---|---|---|---|
| Urbanization | Urbanization rate | Proportion of urban population in the total population (both agricultural and non-agricultural). | 0.99 |
| Population | Permanent resident population | Population living in the area for more than 6 months of the year, including the permanent floating population in the city. | 0.88 |
| Economic development level | GDP | Final outcome of the production activities of all resident units in a country (or region) at national market prices over a period of time, often recognized as the best indicator of the state of a country's economy. | 0.87 |
| Industrialization level | Industrial added value | Final result of industrial production activities expressed in monetary form by industrial enterprises in the region during the reporting period; as the balance after deducting the value of material products and services consumed or transferred in the process of production. It is the newly added value in the production process of industrial enterprises. | 0.77 |
| Livestock and poultry breeding | Major meat production | Production of cattle, sheep, pigs and chicken in the region. | 0.68 |

*$n$ = 5; $p < 0.01$. The original data were extracted from Kunming statistical bulletins on national economic and social development in 2011, 2012, 2013, 2014, 2015, and 2019.

## 1. Justification of the Selected Ecosystem Services

Dianchi Lake Basin (DLB) is located in the middle of the Yunnan-Guizhou Plateau and belongs to Jinsha River system. It covers an area of approximately 2920 $km^2$. The elevation of DLB is 1755–2825 m above sea level (asl), and average altitude of Dianchi Lake (lake area 330.0 $km^2$) is 1885.0 m asl. The terrain is low in the center of the basin, and high in the surrounding (mountainous) areas, high in the north and low in the south. In 2015, the total area of forest and shrub accounted for 34.1% of the total basin area, or 50.9% of the mountainous area. The carbon storage and sequestration potential is huge in this basin and plays an important role in global carbon balance as a carbon sink. China is committed to reducing its carbon emissions through enhancing energy efficiency, renewable energy, and carbon offsetting actions like forest carbon storage and sequestration. The carbon sink in DLB helps meet the national carbon emissions reduction target. To alleviate the negative social impacts of climate change, the Kunming government wants to invest in forest ecosystems to enhance local carbon storage and sequestration for the human benefit of contributing to the mitigation of global climate change impacts.

Water ecosystem services, in terms of clean and sustaining water supplies and improving water quality, are important human benefits for DLB residents. Dianchi Lake is particularly important, and is known as a 'mother lake'. Kunming is a water-deficient area, with an annual per capital water resource of only 310 $m^3$, 1/19 of the provincial average and 1/80 of the national average. The annual water resource of Dianchi Basin is only 570 million $m^3$, the average annual water shortage is 100 million $m^3$ in a normal year and 200 million $m^3$ in a dry year. Water recharge of Dianchi Lake mainly derives from surface runoff, and, therefore, changes in runoff in the basin have an important impact on the water balance of Dianchi Lake. Since local stakeholders want the human benefit of a continuous water supply to maintain Dianchi Lake levels, we selected water yield as an indicator in this study.

Another major problem in DLB is water pollution leading to poor water quality in Dianchi Lake. The water quality in Dianchi Lake has significantly deteriorated, changing to Category V in the mid-1990s, and below Category V after 2000 [1], severely affecting local residents' lifestyle. Therefore, local stakeholders are highly concerned about water quality and want to invest in ecosystems to improve water quality, specifically for human benefits of drinking water, recreation, fisheries, and temperature regulation. Hence we selected water purification by taking nitrogen export as an indicator.

Soil erosion is a national dilemma in China, especially in Southwest China. It is estimated that nearly 40% of China's territory (about 3.5 million $km^2$) suffers from soil erosion. Dianchi Lake Basin is the area with the strongest human activity in Yunnan Province. At the same time, due to the DLB topography fluctuation, the soil is vulnerable to hydraulic erosion, which intensifies the degree of soil and water loss. In 2010, the total amount of soil erosion in the basin was 2.34 million t, and soil erosion has become a prominent ecological problem in DLB. The area affected by moderate and serious erosion is mainly distributed in the elevation range 1900 to 2100 m and the slope range 5 to 25 °. Given the national significance and high importance of soil erosion in the DLB, local stakeholders want soil erosion control for the resident benefits of: fertile soils for agriculture, food security, mitigation of lake and reservoir siltation, and flood control. Hence we selected soil retention as an indicator.

## 2. InVEST Models

The InVEST (Version.3.7.0) suite of models has been designed to enable decision makers to assess trade-offs among and within ecosystem services and to compare the consequences of different scenarios in future, for example those related to land use or climate changes [2]. In the present study, we selected the carbon storage and sequestration model (for carbon storage), the water yield model (for water yield service), the sediment delivery ratio model (for soil retention service), and the nutrient delivery ratio model (for nitrogen export), to evaluate the corresponding ecosystem services in DLB.

*2.1. Carbon Storage and Sequestration (CSS) Model*

Using maps of land use and land cover types, and data on the amount of carbon stored in carbon pools, this model estimates the net amount of carbon stored in a land parcel over time as:

$$C_{total} = C_{above} + C_{below} + C_{soil} + C_{dead} \quad (1)$$

where $C_{total}$ is the total amount (Mg/ha) of carbon storage; and $C_{above}$, $C_{below}$, $C_{soil}$, and $C_{dead}$ represents the amount (Mg/ha) of carbon stored in aboveground biomass, belowground biomass, soil, and dead organic matter, respectively.

*2.2. Water Yield (WY) Model*

Annual water yield for pixel $i$ on land use and land cover (LULC) $j$, $Y_{ij}$ (mm/yr), is estimated based on mean annual precipitation and the Budyko curve:

$$Y_{ij} = (1 - \frac{AET_i}{P_i}) \cdot P_i \quad (2)$$

where $AET_{ij}$ (mm/yr) is actual annual evapotranspiration for pixel $i$ on LULC $j$ and $P_i$ (mm/yr) is annual precipitation for pixel $i$.

For vegetated LULC, the evapotranspiration portion of the water balance, $\frac{AET_i}{P_i}$, is based on an expression of the Budyko curve proposed by Fu et al. (1981) and Zhang et al. (2004):

$$\frac{AET_i}{P_i} = 1 + \frac{PET_i}{P_i} - [1 + (\frac{PET_i}{P_i})^{\omega}]^{\frac{1}{\omega}} \quad (3)$$

where $PET_{ij}$ is potential evapotranspiration and $\omega_i$ is a non-physical parameter that characterizes the natural climate-soil properties.

Potential evapotranspiration, $PET_{ij}$, is defined as:

$$PET_i = K_{c,j} \cdot ET_{0,i} \quad (4)$$

where $ET_{0,i}$ is the reference evapotranspiration from pixel $i$ and $k_{ij}$ is the vegetation evapotranspiration coefficient associated with the pixel $i$ on LULC $j$:

$$\omega_i = Z \cdot \frac{AWC_i}{P_i} + 1.25 \quad (5)$$

$$AWC_i = Min(Rest\_layer\_depth_i, Root\_depth_i) \cdot PAWC_i \quad (6)$$

where $\omega_i$ is a non-physical parameter that characterizes the natural climate-soil properties; $Z$ is a dimensionless constant, ranging from 1 to 30, that captures the local precipitation pattern and hydrogeological characteristics; $AWC_i$ (mm) is the volumetric plant-available water content; 1.25 is the minimum value of $\omega_i$ (Donohue *et al.*, 2012); $k_{ij}$ is the evapotranspiration coefficient for pixel $i$ on LULC $j$; $ET_{0_i}$ (mm/yr) is the reference evapotranspiration for pixel $i$; and $PAWC$ (mm) is the plant-available water capacity.

For non-vegetated LULC (e.g., water, construction land), the actual annual evapotranspiration is computed directly from the reference evapotranspiration and has an upper limit defined by the precipitation:

$$AET_{ij} = Min(k_{ij} \times ET_{0_i}, P_i) \tag{7}$$

where $k_{ij}$ is the evapotranspiration coefficient for pixel $i$ on LULC $j$; $ET_{0_i}$ (mm/yr) is the reference evapotranspiration for pixel $i$ and $P_i$ (mm/yr) is the annual precipitation for pixel $i$.

*2.3. Sediment Delivery Ratio (SDR) Model*

The InVEST sediment delivery model is designed to map overland sediment generation and delivery to the stream. The sediment export from a pixel $i$, $Export_i$ (ton ha$^{-1}$ yr$^{-1}$), and the total sediment export of the evaluated area, $Export_{tot}$ (ton·ha$^{-1}$·yr$^{-1}$), is given by:

$$\begin{aligned} Export_i &= usle_i \cdot SDR_i \\ Export_{tot} &= \sum_i Export_i \end{aligned} \tag{8}$$

The amount of annual soil loss on pixel $i$, $usle_i$, is given by the revised universal soil loss equation (usle):

$$usle_i = R_i \cdot K_i \cdot LS_i \cdot C_i \cdot P_i \tag{9}$$

where $R_i$ (MJ mm (ha hr)$^{-1}$) is the rainfall erosivity; $K_i$ (ton ha hr (MJ ha mm)$^{-1}$) is the soil erodibility; $LS_i$ is the slope length-gradient factor; $C_i$ is the crop-management factor; and $P_i$ is the support practice factor.

The connectivity index, $IC$, is given by:

$$IC = \log_{10}\left(\frac{D_{up}}{D_{dn}}\right) \tag{10}$$

$D_{up}$ is the upslope component defined as:

$$D_{up} = \overline{C}\overline{S}\sqrt{A} \tag{11}$$

where $\overline{C}$ is the average $C$ factor of the upslope contributing area; $\overline{S}$ (m/m) is the average slope gradient of the upslope contributing area; $A$ (m$^2$) is the upslope contributing area; and $D_{dn}$ is the downslope component, defined as:

$$D_{dn} = \sum_i \frac{d_i}{C_i S_i} \tag{12}$$

where $C_i$ and $S_i$ are the $C$ factor and the slope gradient on pixel $i$; and $d_i$ (m) is the length of the flow path along pixel $i$.

The $SDR$ for pixel $i$, $SDR_i$, is derived from the connectivity index $IC$:

$$SDR_i = \frac{SDR_{\max}}{1+\exp\left(\frac{IC_0 - IC_i}{k}\right)} \tag{13}$$

where $SDR_{\max}$ is the maximum theoretical $SDR$; and $IC_0$ and $k$ are calibration parameters that define the shape of the *SDR-IC* relationship.

*2.4. Nutrient Delivery Ratio (NDR) Model*

The InVEST nutrient delivery ratio model maps nutrient sources from watersheds and nutrient transport to streams. Nutrient export from each pixel is calculated based on the product of the load and $NDR$:

$$\begin{aligned} X_{\exp ort_i} &= load_{surf,i} \times NDR_{surf,i} + load_{subs,i} \times NDR_{subs,i} \\ X_{\exp ort_{tot}} &= \sum_i X_{\exp ort_i} \end{aligned} \tag{14}$$

Each pixel's load is modified to account for the local runoff potential, which can be divided into surface and subsurface runoff. The ratio between these two types of nutrient sources is given by the parameter $proportion\_subsurface_i$; therefore, the $load$ (kg·ha$^{-1}$·yr$^{-1}$) for pixel $i$ is defined as:

$$\begin{aligned} load_{surf,i} &= (1 - proportion\_subsurface_i) \times \text{mod}ified\_load_i \\ load_{subsurf,i} &= proportion\_subsurface_i \times \text{mod}ified\_load_i \end{aligned} \tag{15}$$

$$\begin{aligned} \text{mod}ified\_load_i &= load_i \times RPI_i \\ RPI_i &= \frac{RP_i}{RP_a} \end{aligned} \tag{16}$$

where $RPI_i$ is the runoff potential index for pixel $i$; $RP_i$ is the nutrient runoff proxy for runoff on pixel $i$; and $RP_a$ is the average $RP$ over the entire area.

The delivery ratios ($NDR_{surf,i}$ and $NDR_{subs,i}$) are computed based on the concept of the nutrient delivery ratio.

*(1) Surface NDR*

The surface $NDR$ is the product of a delivery factor, representing the ability of downstream pixels to transport nutrients without retention, and a topographic index, representing the position on the landscape. For pixel $i$:

$$NDR_{surf,i} = NDR_{0,i}\left(1+\exp\left(\frac{IC_i - IC_0}{k}\right)\right)^{-1} \tag{17}$$

where $IC_0$ and $k$ are calibration parameters; $IC_i$ is a topographic index; and $NDR_{0,i}$ is the proportion of nutrient that is not retained by downstream pixels (irrespective of the position of the pixel on the landscape).

$$NDR_{0,i} = 1 - eff_i' \tag{18}$$

$$eff_i^{'} = \begin{cases} eff_{LULC_j} \cdot (1 - s_i) & if\ down_i\ is\ a\ stream\ pixel \\ eff_{down_i}^{'} \cdot s_i + eff_{LULC_j} \cdot (1 - s_i) & if\ eff_{LULC_j} > eff_{down_i}^{'} \\ eff_{down_i}^{'} & otherwise \end{cases} \quad (19)$$

where $eff_i^{'}$ is retention efficiency for pixel $i$; $eff_{LULC_j}$ is the maximum retention efficiency that $LULC_j$ can reach; $eff_{down_i}^{'}$ is the effective downstream retention on the pixel directly downstream from pixel $i$; and $s_i$ is the step factor, defined as:

$$s_i = \exp(\frac{1 - 5l_{i_{down}}}{l_{LULC_i}}) \quad (20)$$

where $l_{i_{down}}$ is the length of the flow path from pixel $i$ to its downstream neighbor; and $l_{LULC_i}$ is the LULC retention length of the land cover type on pixel $i$.

$IC$ is the index of connectivity:

$$IC = \log_{10}(\frac{D_{up}}{D_{dn}})$$
$$D_{up} = \overline{S}\sqrt{A}, \quad D_{dn} = \sum_i \frac{d_i}{S_i} \quad (21)$$

where $\overline{S}$ (m/m) is the average slope gradient of the upslope contributing area; $A$ (m$^2$) is the upslope contributing area; and $d_i$ (m) is the length of the flow path along pixel $i$.

*(2) Subsurface NDR*

$$NDR_{subs,i} = 1 - eff_{subs}(1 - e^{\frac{-5l_i}{l_{subs}}}) \quad (22)$$

where $eff_{subs}$ is the maximum nutrient retention efficiency that can be achieved through subsurface flow; $l_i$ is the distance from the pixel to the stream; and $l_{subs}$ is the subsurface flow retention length (i.e., the distance after which it can be assumed that soil retains the nutrient at its maximum capacity).

## 3. InVEST Parameterization

**Table S2.** Data requirements for the InVEST models. CSS = carbon storage and sequestration model; WY = water yield model; SDR = sediment delivery ratio model; NDR = nutrient delivery ratio model.

| Data | Type | Data Source | Note | Related Model |
|---|---|---|---|---|
| Digital Elevation Model | Raster | http://www.gscloud.cn/ http://www.resdc.cn | Resolution is 90 m × 90 m | NDR, SDR |
| Annual average precipitation | Raster | http://data.cma.cn/site/index.html?tdsourcetag=s_pcqq_aiomsg | Resolution is 90 m × 90 m | WY, NDR, SDR |
| Reference evapo-transpiration | Raster | http://www.cgiar-csi.org/data/global-aridity-and-pet-database | Resolution is 90 m × 90 m | WY |

| | | | | |
|---|---|---|---|---|
| Plant-available water content | Raster | Defined according to the LULC and InVEST user's guide | Resolution is 90 m × 90 m | WY |
| Land use/land cover | Raster | http://www.resdc.cn | LULC in 1995 and 2015, including forest, shrub, grass, open water, agriculture, constructed, bare. Resolution is 90 m × 90 m | WY, NDR, SDR, CSS |
| Depth to root restricting layer | Raster | Defined according to the LULC and InVEST user's guide | Resolution is 90 m × 90 m | WY |
| Watersheds | Shape file | http://ngcc.sbsm.gov.cn/article/xxfw/bgxz/ | Shapefile determined by DEM raster using ArcGIS tool | WY, NDR, SDR |
| Rainfall erosivity index | Raster | Defined according to the literature[3] and mean annual precipitation | Resolution is 90 m × 90 m | SDR |
| Soil erodibility | Raster | Standards for classification and gradation of soil erosion (SL190–2007) | Resolution is 90 m × 90 m | SDR |
| Biophysical table | CSV file | – | Including attributes of each LULC, Kc (plant evapotranspiration coefficient), load of nutrients, efficiency of nutrient retention, etc. | WY, SDR, NDR, CSS |

**Table S3.** Key parameters used in the present study.

| Parameter | Description | Computation |
|---|---|---|
| Kc | Evapotranspiration coefficient for each pixel | Defined according to the InVEST user's guide |
| Load_*n* | Load of nitrogen for each LULC | Defined according to the InVEST user's guide |
| Eff_*n* | The maximum retention efficiency of nitrogen for each LULC, varying between 0 and 1. | Defined according to the InVEST user's guide |
| C_above | Aboveground carbon values for each LULC | Defined according to the literature data[4–6] |
| C_below | Belowground carbon values for each LULC. | Defined according to the literature data[4–6] |
| C_soil | Dead carbon value for each LULC. | Defined according to the literature data[4–6] |
| C_dead | Soil carbon values for each LULC. | Defined according to the literature data[4–6] |

**Table S4.** Critical parameter settings in the biophysical attributes table.

| LULC_desc | Kc | Root_depth | C_above | C_below | C_soil | C_dead | usle_c | usle_p | sedret_eff | Load_*n* | Eff_*n* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Forest** | 1 | 7000 | 39.63 | 10 | 42.4 | 40 | 0.003 | 0.2 | 0.6 | 2.8 | 0.8 |
| **Shrub** | 0.85 | 4570 | 9.303 | 2 | 25.6 | 3 | 0.01 | 0.2 | 0.5 | 2 | 0.8 |
| **Grass** | 0.65 | 2000 | 6 | 0.75 | 18.2 | 5.2 | 0.02 | 0.25 | 0.4 | 8 | 0.75 |
| **Open water** | 1 | 1000 | 0 | 0 | 0 | 0 | 0.001 | 0.001 | 0.8 | 0.001 | 0.05 |
| **Agriculture** | 0.6 | 700 | 5 | 1 | 25.6 | 0 | 0.5 | 0.4 | 0.25 | 100 | 0.5 |
| **Constructed** | 0.3 | 500 | 0 | 0 | 21 | 0 | 0.001 | 0.001 | 0.05 | 10 | 0.05 |
| **Bare** | 0.2 | 10 | 0 | 0 | 8.6 | 0 | 0.25 | 0.01 | 0.2 | 4 | 0.05 |

**Table S5.** Land use and land cover classes used in the maps for Dianchi Lake Basin.

| Code | Class/Value | Description |
|---|---|---|
| 1 | Forest | All areas characterized by tree cover (natural or semi-natural woody vegetation, generally greater than 6 m tall); tree canopy accounts for 25–100% of the cover. |
| 2 | Shrub | Areas dominated by shrubs; less than 5 m tall with shrub canopy typically greater than 20% of total vegetation. This class includes true shrubs, young trees in an early successional stage, and trees stunted from environmental conditions. |
| 3 | Grass | Refers to all kinds of grassland mainly growing herbaceous plants, covering more than 5%, including shrubby grassland mainly for grazing and open forest and grass land with canopy density below 10%. |
| 4 | Open water | All areas of open water, generally with less than 25% vegetation or soil cover. |
| 5 | Agriculture | Includes cultivated crops, described as areas used for the production of annual crops, such as corn, soybean, vegetables, tobacco, and cotton. This class also includes all actively tilled land. |
| 6 | Constructed | Includes developed open spaces with a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses such as large-lot single-family housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes. Also included are lands of low, medium, and high intensity development with a mixture of construction forms and vegetation, such as single-family housing units, multi-family housing units, and areas of retail, commercial, and industrial uses. |

**Table S6.** Land use composition in the whole Dianchi Lake Basin (DLB) and in the lakeside and mountainous areas in 1995, as percentage area (%) and total area ($km^2$).

| . | **Whole DLB** | | **Lakeside Area** | | **Mountainous Area** | |
|---|---|---|---|---|---|---|
| | Area | Percent | Area | Percent | Area | Percent |
| Forest | 511.56 | 17.50 | 6.59 | 0.68 | 504.97 | 25.81 |
| Shrub | 499.80 | 17.10 | 10.84 | 1.12 | 488.96 | 24.99 |
| Grass | 569.78 | 19.50 | 66.23 | 6.86 | 503.55 | 25.73 |
| Open water | 343.50 | 11.75 | 322.71 | 33.42 | 20.79 | 1.06 |
| Agriculture | 723.97 | 24.77 | 328.67 | 34.04 | 395.31 | 20.20 |
| Constructed | 273.89 | 9.37 | 230.62 | 23.88 | 43.28 | 2.21 |
| **Total** | 2922.50 | 100.00 | 965.65 | 100.00 | 1956.85 | 100.00 |

**Table S7.** Land use composition in the whole Dianchi Lake Basin (DLB) and in the lakeside and mountainous areas in 2015, as percentage area (%) and total area ($km^2$).

| . | **Whole DLB** | | **Lakeside Area** | | **Mountainous Area** | |
|---|---|---|---|---|---|---|
| | Area | Percent | Area | Percent | Area | Percent |
| Forest | 515.50 | 17.64 | 6.09 | 0.63 | 509.41 | 26.02 |
| Shrub | 488.08 | 16.70 | 8.96 | 0.93 | 479.12 | 24.47 |
| Grass | 531.83 | 18.20 | 42.88 | 4.44 | 489.96 | 25.03 |
| Open water | 339.90 | 11.63 | 319.00 | 33.03 | 20.90 | 1.07 |
| Agriculture | 634.24 | 21.70 | 249.15 | 25.80 | 385.08 | 19.67 |
| Constructed | 412.94 | 14.13 | 339.57 | 35.16 | 73.38 | 3.75 |
| **Total** | 2922.50 | 100.00 | 965.65 | 100.00 | 1957.85 | 100.00 |

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