Supplementary information of

**Biodiversity loss from freshwater use for China’s electricity generation**

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S1 Estimates of water consumption

We assessed the provincial water consumption factors for thermal power and hydropower generation using the method in Jin et al. \(^1\). Based on the factors, the water consumption of electricity generation in each year is calculated as follows:

\[
WC = \sum_i WC_i = \sum_i (TWC_i + HWC_i) = \sum_i (TF_i \cdot TP_i + HF_i \cdot HP_i)
\]  

(1)

In which, \(WC\) gives the national water consumption for electricity generation (m\(^3\)); \(WC_i\) the water consumption for electricity generation in provinces \(i\) (m\(^3\)); \(TWC_i\) the water consumption for thermal power generation in province \(i\) (m\(^3\)); \(HWC_i\) the water consumption for hydropower generation in province \(i\) (m\(^3\)); \(TF_i\) the water consumption factor for thermal power generation in province \(i\) (m\(^3\)/GWh); \(HF_i\) the water consumption factor for hydropower generation in province \(i\) (m\(^3\)/GWh); \(TP_i\) the thermal power generation in province \(i\) (GWh); \(HP_i\) the hydropower generation in province \(i\) (GWh).

S2 Characterization factors for water consumption

Water consumed for electricity generation is not returned to the river. The influence of reduced flow rates on aquatic biodiversity can be quantified with the global species-discharge model, an index of habitat space, feeding and reproductive opportunities. This model is developed based on native fish species and river discharges in various river basins \(^2\). This model assumes a positive correlation between the number of freshwater fish species and average river discharges at the mouth of river basins.

\[
R = 4.2 \cdot Q^{0.4}_{\text{mouth},i}
\]  

(2)

where \(R\) is the freshwater fish species richness and \(Q_{\text{mouth},i}\) is the annual average river discharge at the river mouth of basin \(i\) (m\(^3\)/s).

The species-discharge relationship can be used to calculate characterization factors for water consumption that specify freshwater fish species loss per unit of reduced river discharge for river basins in different regions. Characterization factors (CF\(_c\)) for
water consumption reflect the impact of water use due to human activities on freshwater biodiversity loss.

\[ CF_{c,i} = FF_i \cdot EF_i = \frac{dQ_{\text{mouth},i}}{dW_i} \cdot \left( \frac{dPDF_i}{dQ_{\text{mouth},i}} \cdot V_i \right) \tag{3} \]

where \( FF_i \) is the fate factor of river basin \( i \), \( EF_i \) is the effect factor of river basin \( i \) \( (\text{PDF} \cdot \text{m}^3 \cdot \text{yr}^{-1} \cdot \text{m}^{-3}) \), \( dQ_{\text{mouth},i} \) is the marginal change in water discharge at the river mouth in basin \( i \) \( (\text{m}^3 \cdot \text{yr}^{-1}) \), \( dW_i \) is the marginal change in water consumption by human activities in river basin \( i \) \( (\text{m}^3 \cdot \text{yr}^{-1}) \), \( dPDF_i \) is the marginal change in the potentially disappeared fraction of the freshwater fish species due to the marginal river discharge change \( dQ_{\text{mouth},i} \) and \( V_i \) is the volume of river basin \( i \) \( (\text{m}^3) \). The \( dQ_{\text{mouth},i}/dW_i \) is assumed to be equal to one, indicating that a change in water consumption is fully reflected in a change in water discharge at the mouth for that river basin.

\[ \frac{dPDF_i}{dQ_{\text{mouth},i}} = \frac{dR_i}{dQ_{\text{mouth},i}} = \frac{4.2 \cdot 0.4 \cdot Q_{\text{mouth},i}^{0.4} - 1}{4.2 \cdot Q_{\text{mouth},i}^{0.4}} = \frac{0.4}{Q_{\text{mouth},i}} \tag{4} \]

The river volumes \( (\text{m}^3) \) for all river basins are calculated according to Hanafiah et al. \( ^3 \) as follows:

\[ V_i = 0.47 \cdot \left( \frac{Q_{\text{mouth},i}}{2} \right)^{0.9} \cdot L_i \tag{5} \]

where \( V_i \) is the water volume in river basin \( i \) \( (\text{m}^3) \), \( Q_{\text{mouth},i} \) is the discharge at the river mouth in basin \( i \) \( (\text{m}^3 \cdot \text{yr}^{-1}) \), \( L_i \) is the length of river \( i \) \( (\text{m}) \).

China can be divided into the following river basins: Huaihe, Haihe, Yellow, Yangtze, Pearl, Southeast, Southwest, Continental, Songhua and Liaohe river basins. The characterization factors are calculated for these river basins. Specifically, Qiantang and Min rivers are the representatives of the Southeast river basin. The characterization factors of Qiantang and Min river basins are calculated for Zhejiang and Fujian provinces since they are the largest river basins of the two provinces, respectively \( ^4, 5 \). Talimu is the largest river in the Continental basin, and its characterization factor is calculated for this basin. In terms of Southwest, Brahmaputra is the largest river basin of Tibet, and its characterization factor is calculated for Tibet \( ^6 \). Nandu river is the largest river of Hainan province, and its
characterization factor is calculated for Hainan. The discharges at the river mouth and the river length are obtained from the Ministry of Water Resources\textsuperscript{4,7-9}.

**S3 Thermal pollution of power production**

**S3.1 Thermal pollution from thermal power**

In power plants with once-through cooling systems, water from a freshwater body is used to absorb heat from the working fluid in the condenser. The entire volume of heated water is then discharged back into the water body. In the Rankine cycle of steam-electric generating units, pumps and boilers add heat to liquid water, which is converted into steam during that process. The high-pressure steam then expands in the turbine producing power. Upon exiting the turbine, the steam passes through the condenser where heat is rejected from the system turning the working fluid into a saturated liquid, ready to re-enter the pump. To calculate the rate of heat rejected in each cycle, the difference in enthalpy of the working fluid on either side of the condenser must be multiplied by the steam flow rate. The thermal pollution to water bodies from thermal power is calculated using the method of Raptis and Pfister\textsuperscript{10}.

The heat rejection rates of thermal power are assessed as follows:

\[ Q_t = LF \cdot m_{steam}(h_b - h_a)/1000 \]  \hspace{1cm} (6)

Where \( Q \) is the heat rejection rate (MW), \( LF \) is the load or capacity factor of electricity generating units, which are derived from Jin et al.\textsuperscript{11}, \( m_{steam} \) is the steam flow rate at the high-pressure turbine (kg/s), \( h_b - h_a \) is the difference in enthalpy of the working fluid on either side of the condenser (kJ/kg).

The steam flow rate can be calculated as:

\[ m_{steam} = \beta \cdot C_{gross} \]  \hspace{1cm} (7)

Where \( C_{gross} \) is the gross generating capacity (MW) and \( \beta \) is a constant (0.830 kg s\textsuperscript{-1} MW\textsuperscript{-1} \textsuperscript{10}).

Reheat cycles can be added into the Rankine cycle, increasing the generation efficiency and thus reducing fuel inputs. When reheat cycles are employed, the steam passes first through a high-pressure turbine and, after being reheated, through a low-
pressure turbine. 94% of China’s units with an installed capacity of 100-220 MW use a reheat system, whereas all 300-1000 MW units use a reheat system. For a reheat system, the ratio \((r)\) of the steam flow at the entry of low-pressure turbine to the steam flow at the entry of high-pressure turbine is inserted to scale the rejection rate:

\[
Q_t = LF \cdot m_{steam} \cdot r \cdot (h_b - h_a)/1000
\]

Where \(r=0.85\) is used for China’s units in this study, referring to Yan et al. and Cheng et al. \(h_a\) is related to the water temperature withdrawn for use in the condenser. An additional necessary piece of information for all thermodynamic cycles is the temperature of the freshwater withdrawn for use in the condenser. To obtain these values, the georeferenced power plants are overlaid onto gridded estimates (at 10 km spatial resolution) of water temperatures. The average over 15 years (2000-2014) is used to minimize the impacts of very warm or very cold years on the water temperature estimates. For every generating unit then, mean monthly naturalized water temperatures are extracted. The information on power plants is sourced from the China Electricity Council, Global Coal Plant Tracker, World Electric Power Plants Database and our previous study. The results of plant-level thermal pollution and its impacts are then aggregated to the provincial level.

**S3.2 Thermal pollution from hydropower**

Hydropower also produces heat during operation, though its thermal pollution is smaller than that of thermal power with a once-through cooling system because of its higher energy efficiency. The thermal emission of hydropower can be calculated as follows:

\[
Q_h = LF \cdot C_{gross} \cdot HR
\]

Where \(HR\) is the heat emission rate of China’s hydropower, referring to Xu et al. and Yan and Hao; here, \(HR\) is 1.8%. The definitions of \(LF\) and \(C_{gross}\) are the same as those in Equations 7-9.

There are approximately 47,000 hydropower stations in China. It is infeasible to assess the thermal emission and biodiversity impacts at the plant level because of data limitations. We made assessments at the provincial level by changing equation 10 to
Where \( LF_p \) is the provincial load or capacity factor of hydropower, \( C_p \) is the provincial installed capacity of hydropower (MW). The values of \( LF_p \) and \( C_p \) are obtained from the National Bureau of Statistics 21.

S4 Biodiversity impacts assessments

**Biodiversity loss caused by freshwater consumption:** Electricity generation can cause aquatic biodiversity loss because of its water use 22, 23. Surface water consumption impacts aquatic biodiversity. Water consumption is translated to impacts on aquatic biodiversity by characterization factors expressed as a potentially disappeared fraction of species (unit: PDF m\(^3\) yr /m\(^3\) ) 3.

\[
WBL_i = WC_i \cdot CF_{c,i} \tag{11}
\]

Where \( WBL_i \) gives the biodiversity loss caused by water consumption for electricity generation in province \( i \) (PDF m\(^3\) yr); \( WC_i \) the water consumption for electricity generation in province \( i \) (m\(^3\)); \( CF_{c,i} \) the biodiversity loss per unit of water consumption for electricity generation in province \( i \) (PDF m\(^3\) yr/m\(^3\)).

**Biodiversity loss caused by thermal emissions:** The factor of local biodiversity impacts from thermal emissions is obtained from Raptis et al. 23.

The biodiversity loss caused by electricity generation is calculated as follows:

\[
TBL_i = TBLT_i + TBLH_i = \sum_{n} Q_{t,n,i} \cdot TBF_{n,i} + Q_{h,i} \cdot PTBF_i \tag{12}
\]

Where \( TBL_i \) gives the biodiversity loss caused by thermal emissions of electricity generation in province \( i \) (PDF m\(^3\) yr); \( TBLT_i \) the biodiversity loss caused by thermal emissions from thermal power in province \( i \) (PDF m\(^3\) yr); \( TBLH_i \) the biodiversity loss caused by thermal emissions from hydropower in province \( i \) (PDF m\(^3\) yr); \( Q_{t,n,i} \) the thermal emissions from the thermal power plant \( n \) in province \( i \) (MJ); \( TBF_{n,i} \) the biodiversity loss per unit of thermal emissions from the thermal power plant \( n \) in province \( i \) (PDF m\(^3\) yr/MJ); \( n \) the thermal power plants with once-through cooling systems in
province $i$: $Q_h_i$, the thermal emissions from hydropower in province $i$ (MJ); $PTBF_i$, the biodiversity loss per unit of thermal emissions in province $i$ (PDF m$^3$ yr/MJ); the characterization factors are derived from Raptis et al. $^{23}$, where global gridded freshwater thermal pollution CFs are assessed. We extract the gridded CFs for thermal power and China’s CFs for hydropower at monthly resolution.

**S5 Estimates of water stress**

The Water Stress Index is calculated according to Pfister et al. $^{24}$, which is adapted from the water withdrawal-to-availability indicator by applying a logistic function to acquire continuous values between 0.01 and 1. The equation is as follows:

$$ WSI = \frac{1}{1 + e^{-6.4 \cdot WTA^* \left(\frac{1}{0.01} - 1\right)}} $$

Where $WSI$ is the water stress index. $WTA^*$ is a modified $WTA$ indicator considering the difference for watersheds with and without strongly regulated flows. Four levels of water stress are classified in the $WSI$, i.e. minor (0.01-0.09); moderate (0.09-0.5); severe (0.5-0.91); and extreme (0.91-1). The water stress indexes are calculated for 2017 based on the water withdrawal and availability from the Ministry of Water Resources $^{25}$.

**S6 Converting local impacts to global impacts**

Kuipers et al. estimated global extinction probabilities (GEPs) based on species range sizes, species vulnerabilities, and species richness, indicating to what extent regional species loss in the respective area may contribute to global species loss. They generate them for marine, terrestrial, and freshwater species groups on the local (i.e., 0.05° × 0.05° grid) and ecoregion scale $^{26}$. The regional fractions of freshwater species losses are then multiplied with the corresponding GEPs to calculate potential global fractions of extinctions:

$$ GBL_i = BL_i/V_i \cdot GEP_i $$

Where $GBL_i$ gives the potential global biodiversity loss in province $i$ (PDF yr); $V_i$ is
the volume of the representative river in province $i$; $GEP_i$ is the global extinction probability in province $i$, calculated by aggregating the cell-level GEPs from Kuipers et al. 26 within province $i$. 
Supplementary figures

**Supplementary Figure S1.** The decoupling state quadrant map corresponding to the decoupling degree. Here, $BL = \Delta BL/BL_{t-1}$, $EG = \Delta EG/EG_{t-1}$. This map is modified from Tapio 27.

**Supplementary Figure S2.** China’s provinces.
Supplementary Figure S3. The electric power mix in China.

Supplementary Figure S4. The biodiversity loss by freshwater use for China’s electricity generation during 2008-2017.

Supplementary Figure S5. The total amount of interprovincial power transmission in China.
Supplementary tables

**Supplementary Table S1.** The provincial characterization factors of water consumption impacts on local biodiversity.

| Province       | Characterization factor (PDF·m³ yr⁻¹ m⁻³) | Province       | Characterization factor (PDF·m³ yr⁻¹ m⁻³) |
|----------------|--------------------------------------------|----------------|--------------------------------------------|
| Beijing        | 1.76E-03                                   | Hubei          | 7.19E-03                                   |
| Tianjin        | 1.76E-03                                   | Hunan          | 7.19E-03                                   |
| Hebei          | 1.76E-03                                   | Guangdong      | 2.78E-03                                   |
| Shanxi         | 8.17E-03                                   | Guangxi        | 2.78E-03                                   |
| Inner Mongolia | 8.17E-03                                   | Hainan         | 5.79E-04                                   |
| Liaoning       | 2.51E-03                                   | Chongqing      | 7.19E-03                                   |
| Jilin           | 2.84E-03                                   | Sichuan        | 7.19E-03                                   |
| Heilongjiang   | 2.84E-03                                   | Guizhou        | 7.19E-03                                   |
| Shanghai       | 7.19E-03                                   | Yunnan         | 3.99E-03                                   |
| Jiangsu        | 7.19E-03                                   | Xizang         | 2.79E-03                                   |
| Zhejiang       | 6.76E-04                                   | Shaanxi        | 8.17E-03                                   |
| Anhui          | 7.19E-03                                   | Gansu          | 8.17E-03                                   |
| Fujian         | 8.14E-04                                   | Qinghai        | 8.17E-03                                   |
| Jiangxi        | 7.19E-03                                   | Ningxia        | 8.17E-03                                   |
| Shandong       | 1.50E-03                                   | Xinjiang       | 3.34E-03                                   |
| Henan          | 1.50E-03                                   |                |                                            |

**Supplementary Table S2.** The provinces’ full names and abbreviations used in Figure 4.

| Full name  | Abbreviation | Full name  | Abbreviation |
|------------|--------------|------------|--------------|
| Anhui      | AH           | Liaoning   | LN           |
| Beijing    | BJ           | Inner Mongolia | NM       |
| Fujian     | FJ           | Ningxia    | NX           |
| Gansu      | GS           | Qinghai    | QH           |
| Guangdong  | GD           | Shandong   | SD           |
| Guangxi    | GX           | Shanxi     | SX           |
| Guizhou    | GZ           | Shaanxi    | SN           |
| Hainan     | HI           | Shanghai   | SH           |
| Hebei      | HE           | Sichuan    | SC           |
| Henan      | HA           | Tianjin    | TJ           |
| Heilongjiang | HL         | Xizang     | XZ           |
| Hubei      | HB           | Xinjiang   | XJ           |
| Hunan      | HN           | Yunnan     | YN           |
| Jilin      | JL           | Zhejiang   | ZJ           |
| Jiangsu    | JS           | Chongqing  | CQ           |
| Jiangxi    | JX           |            |              |
**Supplementary Table S3.** The decoupling degree and decoupling state (see Supplementary Figure 1) between biodiversity loss and electricity generation.

| Time period | Decoupling degree | Decoupling state           |
|-------------|-------------------|----------------------------|
| 2008-2009   | 1.4               | Expansive negative decoupling |
| 2009-2010   | 0.39              | Weak decoupling            |
| 2010-2011   | 0.7               | Weak decoupling            |
| 2011-2012   | 0.87              | Expansive coupling         |
| 2012-2013   | 0.8               | Expansive coupling         |
| 2013-2014   | 0.31              | Weak decoupling            |
| 2014-2015   | -0.31             | Strong decoupling          |
| 2015-2016   | 0.52              | Weak decoupling            |
| 2016-2017   | 0.19              | Weak decoupling            |
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