
Contributed Paper

Effectiveness of China's national forest protection program and nature reserves

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Abstract: *There is profound interest in knowing the degree to which China's institutions are capable of protecting its natural forests and biodiversity in the face of economic and political change. China's 2 most important forest-protection policies are its National Forest Protection Program (NFPP) and its national-level nature reserves (NNRs). The NFPP was implemented in 2000 in response to deforestation-caused flooding. We undertook the first national, quantitative assessment of the NFPP and NNRs to examine whether the NFPP achieved its deforestation-reduction target and whether the NNRs deter deforestation altogether. We used MODIS data to estimate forest cover and loss across mainland China (2000–2010). We also assembled the first-ever polygon dataset for China's forested NNRs ($n = 237$, $74,030 \text{ km}^2$ in 2000) and used both conventional and covariate-matching approaches to compare deforestation rates inside and outside NNRs (2000–2010). In 2000, 1.765 million km^2 or 18.7% of mainland China was forested (12.3% with canopy cover of $\geq 70\%$) or woodland (6.4% with canopy cover $< 70\%$ and tree plus shrub cover $\geq 40\%$). By 2010, $480,203 \text{ km}^2$ of forest and woodland had been lost, an annual deforestation rate of 2.7% . Forest-only loss was $127,473 \text{ km}^2$ (1.05% annually). In the NFPP provinces, the forest-only loss rate was 0.62% , which was 3.3 times lower than in the non-NFPP provinces. Moreover, the Landsat data suggest that these loss rates are overestimates due to large MODIS pixel size. Thus, China appears to have achieved, and even exceeded, its target of reducing deforestation to 1.1% annually in the NFPP provinces. About two-thirds of China's NNRs were effective in protecting forest cover (prevented loss 4073 km^2 unmatched approach; 3148 km^2 matched approach), and within-NNR deforestation rates were higher in provinces with higher overall deforestation. Our results indicate that China's existing institutions can protect domestic forest cover.*

Keywords: avoided deforestation, biodiversity conservation, covariate matching, governance, MOD13Q1, national parks, protected areas

La Efectividad del Programa Nacional de Protección de Bosques y las Reservas Naturales en China

Resumen: *Existe un interés profundo por conocer el grado al que las instituciones en China son capaces de proteger sus bosques naturales y biodiversidad de frente al cambio económico y político. Las dos políticas de protección de bosques más importantes de China son el Programa Nacional de Protección de Bosques*

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(PNPB) y las reservas naturales a nivel nacional (RNN). El PNPB se implementó en el 2000 en respuesta a las inundaciones causadas por la deforestación. Emprendimos la primera evaluación cuantitativa a nivel nacional del PNPB y las RNN para examinar si el primero logra su objetivo de reducir la deforestación y si el segundo la impide por completo. Utilizamos datos de MODIS para estimar la cobertura y pérdida de bosque en toda la China continental (2000–2010). También ensamblamos el primer conjunto de datos de polígonos de las RNN boscosas de China ($n = 237$, $74,030 \text{ km}^2$ en 2000) y usamos tanto estrategias convencionales como de correspondencia de covarianza para comparar las tasas de deforestación dentro y fuera de las RNN (2000–2010). En el 2000, 1.765 millones de km^2 , o el 18.7% de la China continental, estaban arbolados (12.3% con una cobertura de dosel $\geq 70\%$) o cubiertos por bosque (6.4% con una cubierta de dosel $< 70\%$ y con cubierta de árboles más arbustos $\geq 40\%$). Para el 2010, ya se habían perdido $480,203 \text{ km}^2$ de bosque, una tasa anual de deforestación del 2.7%. La pérdida del bosque puro fue de $127,473 \text{ km}^2$ (1.05% anualmente). En las provincias del PNPB, la tasa de pérdida del bosque puro fue de 0.62%, lo que fue 3.3 veces más bajo que en las provincias fuera del programa. Además, los datos de Landsat sugieren que estas tasas de pérdida son sobreestimados debido al gran tamaño de pixel de MODIS. Así, China parece haber alcanzado, e incluso excedido, su objetivo de reducir la deforestación a 1.1% anualmente en las provincias del PNPB. Aproximadamente dos tercios de las RNN de China fueron efectivas en la protección de la cobertura del bosque (pérdida prevenida 4073 km^2 con la estrategia sin correspondencia; 3148 km^2 con la correspondencia), y dentro de las RNN, las tasas de deforestación fueron mayores en las provincias con una deforestación mayor en general. Nuestros resultados indican que las instituciones existentes en China pueden proteger la cobertura doméstica de bosque.

Palabras Clave: áreas protegidas, conservación de la biodiversidad, correspondencia de covarianza, deforestación evitada, gobierno, MOD13Q1, parques nacionales

China covers one of the greatest ranges of climates and ecological diversity in the world, in total containing $\sim 10\%$ of all species living on Earth, including over 34,000 vascular plant species and over 7500 vertebrate species, many of which are endemic to China (World Bank 2001a; MEP PRC 2013). Maintaining this high-species diversity is China's large variety of ecosystems, including 212 natural types of forest (World Bank 2001a; MEP PRC 2013). However, China's biodiversity, ecosystem services, and natural landscapes are being degraded at a rapid rate due to swift economic growth and institutional constraints (Economy 2007; Kahn & Yardley 2007; Wang et al. 2007b; Liu et al. 2008). With the decline of its natural forests, China has witnessed deterioration in biodiversity. At least 200 plant species are extinct, 15–20% of China's higher plant species are endangered, 233 vertebrate species are on the edge of extinction, and more than 61% of wildlife species are affected by habitat loss (World Bank 2001a; Liu & Diamond 2005; MEP PRC 2010). In contrast, China has made important political commitments to conservation as a signatory of major international biodiversity treaties and by implementing many domestic conservation laws and regulations and targeting conservation programs for charismatic species such as panda, tiger, primates, and cranes.

Arguably the most important class of conservation measures in China is its forest-protection policies. From 1970 to 1996, when weak forest-protection laws and enforcement prevailed, the annual deforestation rate was approximately 2.67–3.36% (Li & Yang 2000), and this loss contributed to severe soil erosion and flooding (Zhang et al. 2000). In particular, deforestation and cultivation on steep slopes in the upper Yangtze River led to the

devastating 1998 flood (Zong & Chen 2000; Zhang et al. 2001). In response, in 2000 the Natural Forest Protection Program (NFPP) was implemented across 17 provinces in 3 regions: the upper reaches of the Yangtze River, the upper and middle reaches of the Yellow River, and certain "key state-owned forestry regions," as designated by the government (Figs. 1 & 2). Final expenditures on the NFPP reached RMB118.6 billion (\sim US\$19.2 billion) from 2000 through 2010 (SFA PRC 2010a).

One of the NFPP's main objectives was to reduce commercial timber extraction by 62.1% through a ban on commercial logging on $0.445 \text{ million km}^2$ (SFA PRC 2000). Given that the annual logging rate during 1994–1996 across mainland China was 3.0% (Li & Yang 2000), to achieve a 62.1% reduction in logging implies that the annual deforestation rate within the NFPP zone needed to be reduced to 1.1% ($3.0\% \times [1 - 62.1\%]$) during 2000–2010. To judge the NFPP's effectiveness, we can compare China's achieved deforestation rate with this target.

China also protects natural forest within its nature reserve (NR) network. Starting with its first NR in 1956, China had established 2669 NRs by 2012. These reserves cover 14.9% of China's land area ($1.43 \text{ million km}^2$). A total of 363 are national-level nature reserves (NNRs) that account for 62.9% of the area of all NRs (MEP PRC 2013) and are meant to cover the most important and biodiverse ecosystems. Consequently, NNRs receive the highest level of protection and state funding. For example, in 1999 NNRs received $\$113/\text{km}^2$, while other NRs received $\$53/\text{km}^2$ (Liu et al. 2003).

However, the effectiveness of China's NFPP and NNR programs in protecting natural forest is disputed (Liu et al. 2001; Wang et al. 2013). Even the precise borders of the

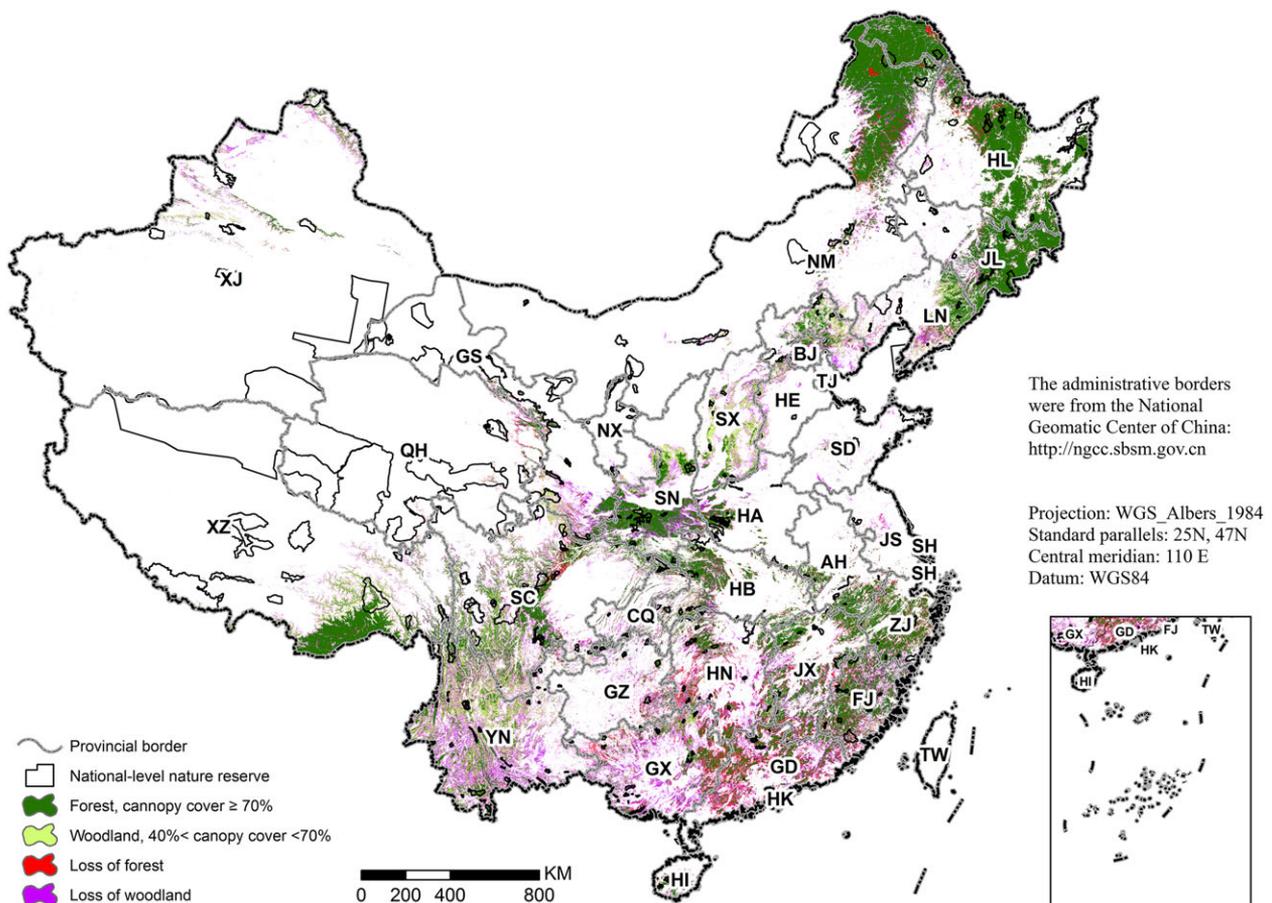


Figure 1. Forest and woodland cover and national-level nature reserves in mainland China in 2000 and loss of this cover in 2000–2010 (AH, Anhui; BJ, Beijing; CQ, Chongqing; FJ, Fujian; GD, Guangdong; GS, Gansu; GX, Guangxi; GZ, Guizhou; HA, Henan; HB, Hubei; HE, Hebei; HI, Hainan; HL, Heilongjiang; HN, Hunan; JL, Jilin; JS, Jiangsu; JX, Jiangxi; LN, Liaoning; NM, Inner Mongolia; NX, Ningxia; QH, Qinghai; SC, Sichuan; SD, Shandong; SH, Shanghai; SN, Shaanxi; SX, Shanxi; TJ, Tianjin; XJ, Xinjiang; XZ, Tibet; YN, Yunnan; ZJ, Zhejiang). A high-resolution version is available in Supporting Information.

NNRs have been mostly unknown to the public, and estimates of China's forest cover from 2000 to 2010 vary by a factor of 1.7 (1,209,000–2,054,056 km²), in part due to varying definitions of *forest* (World Bank 2001b; Hansen et al. 2010; SFA PRC 2005, 2010b). Moreover, because economic development typically takes precedence over biological conservation at local governance levels (Liu & Diamond 2005), it is widely reported that natural forest continues to be cleared or converted to low-biodiversity tree plantations (rubber, *Eucalyptus*, and fruit trees) (Li 2004; Li et al. 2007; Wang et al. 2007b; Xu 2011; Zhai et al. 2012).

Given China's large biodiversity endowment and high level of forest cover and the profound domestic and international interest in knowing the degree to which modern China's governing institutions are capable of protecting biodiversity, we mapped annual forest cover over mainland China from 2000 through 2010 with a

uniform remote sensing dataset (MOD13Q1) and the randomForest algorithm (Breiman 2001; Liaw & Wiener 2002; Bartholome & Belward 2005; Clark et al. 2010); quantified deforestation with a 3-year moving window from 2000 to 2010; used conventional unmatched and covariate-matching analyses (Andam et al. 2008; Joppa et al. 2008) to estimate how much closed forest in the NNRs avoided deforestation during the logging-ban era; and compared our results with the recently released, Landsat-based global dataset of deforestation (Hansen et al. 2013).

We sought to determine whether 2 important nature-protection institutions in China, the NFPP and the NNR system, have been effective. Estimates of forest-cover loss provide rare quantitative measures of effectiveness, due to the NFPP's public, quantitative deforestation reduction targets and because NNR status prohibits deforestation outright.

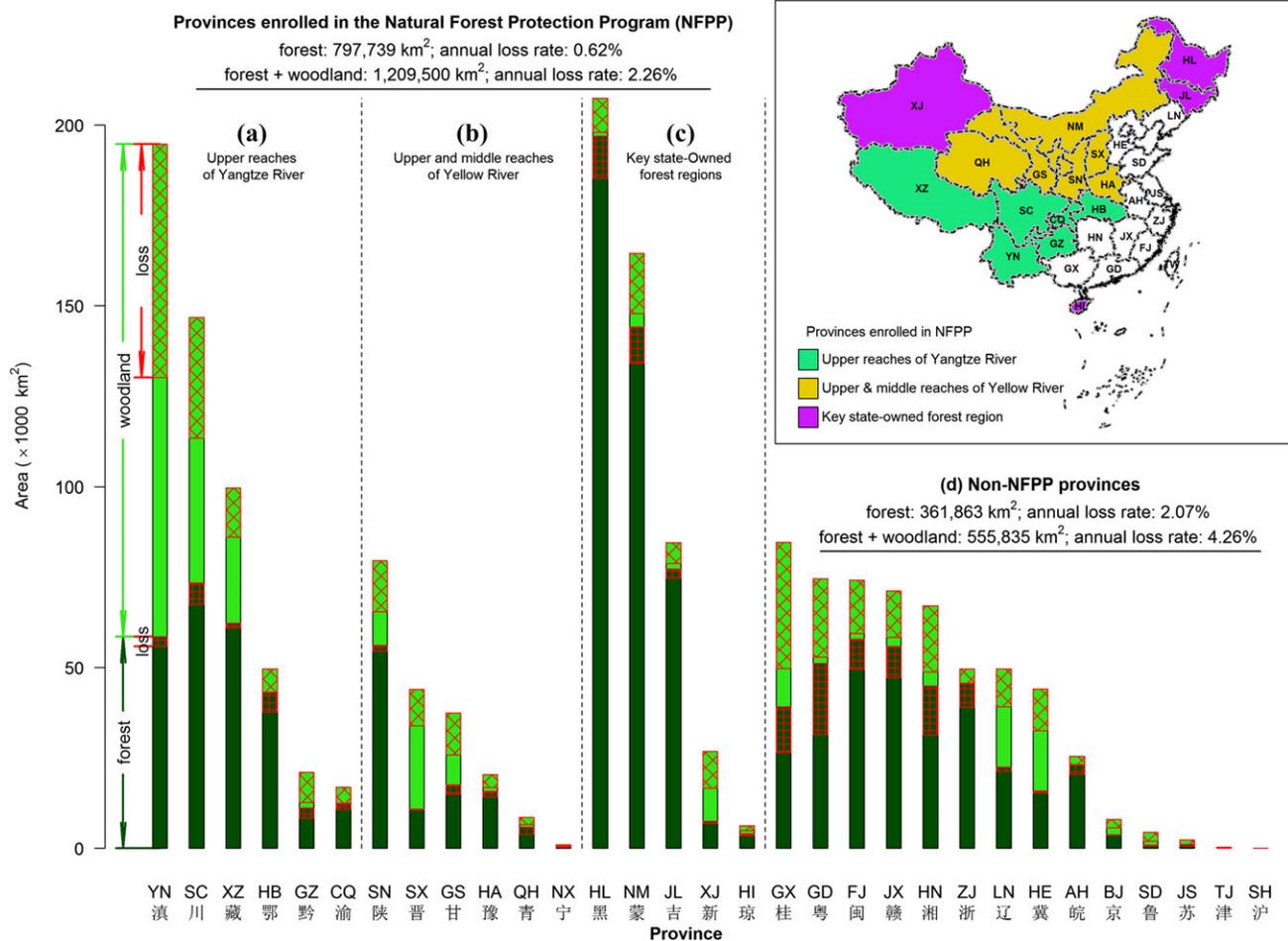


Figure 2. Forest (canopy cover $\geq 70\%$) and woodland (canopy cover $< 40\text{--}69\%$) cover over mainland China in 2000 and the loss of this cover in 2000–2010 by province and by NFPP status: (a) upper reaches of Yangtze River (260,905 km², 0.71%), (b) upper and middle reaches of Yellow River (106,784 km², 0.71%), (c) key state-owned forest regions (430,051 km², 0.55%), and (d) non-NFPP provinces (361,863 km², 2.07%). Inset shows NFPP-enrolled provinces.

Methods

Remote Sensing and Terrain Data

The MOD13Q1 dataset layers we used to map forest cover included a 16-day composite of red, near infrared, and mid-infrared reflectance, Normalized Difference Vegetation Index, and Enhanced Vegetation Index at 231.7 m resolution (Solano et al. 2010). Low-quality pixels due to clouds and shadows were filled by the mean values of the previous and following scenes. In addition, for all of mainland China, we downloaded processed Landsat data (forest extent 2000 and forest loss 2000–2010) from the Global Forest Change site (<http://earthenginepartners.appspot.com/science-2013-global-forest>, accessed 2 Nov 2014). Although 30-m resolution Landsat data were also available, the computing cost of analyzing 11 years of Landsat data would have been prohibitive, and, more importantly, the MOD13Q1 dataset provided 23 scenes of uniform data

each year, while Landsat could not. Thus, the MOD13Q1 data allowed us to confirm that an apparently deforested pixel remained so for 2 years after the event, thereby increasing confidence.

The Shuttle Radar Topography Mission (SRTM) dataset was downloaded from USGS (<http://srtm.usgs.gov/index.php>). Elevation, slope, and a topographic position index (TPI) were calculated from the 90-m resolution SRTM. The TPI of a focal pixel was defined as the difference between its elevation and the mean elevation of all pixels in an 11 × 11 grid centered on the focal pixel. The TPI identifies pixels that are either higher (peaks) or lower (gorges) than the surroundings and thus captures local inaccessibility.

Classification Scheme, Training Data Definition, and Land-Cover Mapping

Using Arc2Earth software (<http://www.arc2earth.com/>) with ArcGIS (Ver. 10.0, ESRI), we synchronized our

MODIS data with high-resolution images in Google Earth (<http://www.google.com/earth>) and then digitized and visually assigned 13,869 polygons (minimal edge > 500 m) to 3 cover classes based on Google Earth images (summer and autumn 2012): forest (tree canopy cover $\geq 70\%$), woodland (tree canopy cover <70% and tree plus shrub cover $\geq 40\%$), and non-wooded land (tree cover <40%, including open shrub, grassland, farmland, urban, open water, etc.). Tree canopy cover was visually estimated by crown perimeter. With 23 scenes of MOD13Q1 product per year, we used the random forest algorithm to classify annual land cover over mainland China from 2000 through 2010 (Breiman 2001; Clark et al. 2010; Dorais & Cardille 2011). For each year, producer's accuracy was $\geq 92\%$.

Deforestation Detection

From 2000 to 2010, we recorded forest loss and ignored any subsequent afforestation because our goal was to measure the effectiveness of the NFPP and NNRs in reducing and preventing the loss, respectively, of already standing forest and because most new afforestation in China is due to low-biodiversity plantations (Chazdon 2008; Rudel 2009; Perfecto & Vandermeer 2010; Xu 2011). We defined *narrow-sense deforestation* (δ_{forest}) as clearance of forest to non-wooded land and *broad-sense deforestation* ($\delta_{\text{forest+woodland}}$) as clearance of forest and woodland to non-wooded land. Broad-sense deforestation is a less reliable measure because it has a higher probability of mis-registration (see Supporting Information for details). For the same reasons, we did not attempt to record conversion of forest to woodland or woodland to forest. We used 3-year moving windows to adjudge forest loss (forest to non-forest, non-woodland). Only if the first year of a window was forest and the next 2 years were non-forest and non-woodland was a pixel classified as deforested in that window. This method is especially useful for cases where forest cover is distributed over small patches relative to MODIS pixel size (231.7 m), as we found for one NNR in Gansu. Mis-registration between consecutive years might make some patches appear to have been deforested and then later reforested.

To assess change-detection accuracy, we sampled 200 deforestation pixels at random in southwestern, southeastern, eastern, and northeastern China that could be independently classified as deforested or not via high-resolution imagery in Google Earth. User accuracy was $\geq 90\%$ in all four regions.

NNR Data and Effectiveness

The Chinese Research Academy of Environmental Sciences delineated and merged boundary polygons of all NNRs on behalf of the Ministry of Environmental Protection (MEP). Data sources were the NNR master plans

finished and reported to the MEP by each NNR under the Regulations on Nature Reserves of China. These polygons are currently the best available data on NNR borders, but boundary accuracies vary due to capacity differences among NNR staff.

We evaluated the effectiveness of the NNRs at the individual reserve level and collectively at the provincial level because NNRs are managed at both levels. At each level, we used both unmatched and matched (covariate-matching) sampling (Andam et al. 2008; Joppa et al. 2008) to estimate δ_{forest} from sampled pixels that were forest in 2000 and to determine if these pixels were deforested (neither forest nor woodland) in 2010. In brief, the unmatched method randomly sampled a set number of forested pixels in 2000 inside the NNR and again outside the NNR (10–100 km from the NNR border) and compared how many pixels inside and outside remained forested in 2010. The matched sampling method also compared a set number of pixels inside and outside the NNRs, but pairs of inside and outside pixels were matched by characteristics such as elevation, slope, and distance to forest edge. The matched method was more effective at isolating the effect of reserve status per se because it controlled for the tendency of reserves to be located in more remote and less productive areas, thus deriving part of their protection from inaccessibility.

At the end of 2012, there were 363 NNRs in mainland China. Of these 241 contained at least 10 km² of forest cover and were distributed over 29 provinces. Of these 241 NNRs, we omitted 4 in 2 provinces (Ningxia and Tianjin) because not enough closed forest could be found outside the reserve to evaluate effectiveness. At the NNR level, we sampled n_1 pixels of forest in 2000 inside an NNR and n_2 pixels outside the NNRs within the province. We calculated n_1 as $\min(1000, 50\% * N_1)$, where N_1 is the total number of forest pixels inside the NNR and n_2 as $\min(10000, 50\% * N_2)$, where N_2 is the total number of forest pixels outside the NNR and all the other NNRs within the province. A 10-km buffer was used to remove leakage effects in which deforestation banned in the reserve spills over to just outside the reserve (Nagendra 2008; Wittemyer et al. 2008) or where deforestation is lower next to reserve borders, possibly due to governance or isolation spillovers (Gaveau et al. 2009; Wang et al. 2013). By restricting pixels to within 100 km of NNRs in the same province, we ensured that matching pixels were chosen from similar bioclimatic regimes. At the provincial level, we also sampled n_1 pixels of forest in 2000 inside all NNRs and n_2 pixels of forest in 2000 outside the NNRs within the province. Where n_1 was the minimum of 2000 and number of forest pixels in 2000 inside all NNRs within the province; n_2 is the minimum of 10,000 and the total forest pixels in 2000 outside all NNRs within the province. The effectiveness of NNRs within a province was calculated as $\text{effectiveness}_{\text{unmatched}} = \text{deforestation rate outside} - \text{deforestation rate inside}$,

where deforestation rate outside = (number of pixels converted to non-forest outside NNR)/ n_2 and deforestation rate inside = (number of pixels converted to non-forest inside NNR)/ n_1 .

For the matched method, our four covariates were elevation above sea level, TPI, slope, and distance to forest edge. For each within-NNR pixel, we found matching outside-NNR pixels (Andam et al. 2008; Nolte et al. 2013) within calipers (allowable differences) of ≤ 200 m of elevation, ≤ 15 m of TPI, and ≤ 5 degrees of slope. The outside-NNR pixel with the shortest Mahalanobis distance was deemed the best match (Andam et al. 2008). For the provincial-level analyses, we resampled 10 times and used the mean. For the individual NNR analyses, we resampled 20 times and used the mean. The effectiveness of NNRs within a province was calculated as $\text{effectiveness}_{\text{matched}} = (\text{mean deforestation rate of matched samples outside all NNRs}) - (\text{mean deforestation rate of matched samples within all NNRs})$.

We also tested NNR effectiveness with Hansen et al.'s (2013) Landsat dataset. To allow comparisons, we aggregated 8*8 of the Hansen et al. tree-cover pixels into 1 Hansen pixel. Therefore, for each Hansen pixel, tree cover was calculated as the mean value of the 64 original pixel values. We did the same for forest-loss pixels. We then ran unmatched and matching analyses for NNRs at the provincial level as we did with the MODIS data (see also Supporting Information).

Results

Forest Cover and Loss 2000–2010 and NFPP Effectiveness

In 2000, 1.765 million km² or 18.7% of mainland China was covered in forest (12.3%) or woodland (6.4%) (Fig. 1). The 17 provinces enrolled in the NFPP contained 68.8% of China's forest cover (Fig. 2). Heilongjiang, Inner Mongolia, Jilin, Sichuan, and Tibet contained 48% of forest cover, and with the addition of Yunnan, Fujian, Shaanxi, Jiangxi, and Guangdong, the total was 72% (Fig. 2).

Most narrow-sense deforestation occurred in the southeast in Guangdong, Hunan, and Guangxi (all non-NFPP). These provinces accounted for 36.0% of δ_{forest} (Figs. 1 & 2). The next two provinces with the highest δ_{forest} values, Heilongjiang and Inner Mongolia, are designated key state-owned forest regions within the NFPP, had the highest proportion of forest cover in the country, and accounted for 17.1% of δ_{forest} from 2000 to 2010 (Fig. 2). For the 27 mainland provinces with forest area larger than 1000 km² in 2000, provincial forest cover did not explain deforestation rate (linear regression, $R^2 = 0.06$, $F_{1,25} = 1.63$, $p = 0.23$).

From 2000 to 2010, $\delta_{\text{forest+woodland}}$ was 480,203 km², or 27.2% of the original forest and woodland cover, resulting in 1.285 million km² or 13.6% of mainland

China remaining under original forest or woodland in 2010. The top 5 provinces for broad-sense deforestation were in the south and southwest, again including the same 3 non-NFPP provinces, Guangdong, Hunan, and Guangxi, and 2 NFPP provinces, Yunnan, and Sichuan, which collectively contributed 47.3% of $\delta_{\text{forest+woodland}}$ (Figs. 1 & 2).

NNR Effectiveness

Of China's 363 NNRs, 237 contained sufficient natural forest both inside and outside their borders to be evaluated. These 237 NNRs, which encompassed 74,030 km² of forest in the 2000, prevented 4073 km² of forest loss (Fig. 3a) (unmatched approach) or prevented 3148 km² of loss (Fig. 3b) (matched approach). The matched and unmatched approaches largely concurred. The unmatched method identified 167 NNRs as effective (i.e., prevented a statistically significant amount of forest loss, $p < 0.05$, paired t test with fdr correction; Supporting Information), and the matched method identified 158 NNRs as effective. Under both methods, 137 NNRs were identified as effective, and 188 NNRs were identified as effective by at least one method (Supporting Information).

We also measured the pooled effectiveness of NNRs at the provincial governance level, including all provinces with forest cover > 1000 km². Thus, Shandong, Jiangsu, Tianjin, and Shanghai, which lacked of 1000 km² forest cover, and Ningxia, where forest cover was almost exclusively located in NNRs, were excluded from the analysis. Pooled NNRs in 23 of 26 provinces effectively ($p < 0.05$, paired t test with fdr correction) protected forest cover, as shown by both approaches (unmatched: 21 of 26; matched: 18 of 26 provinces) (Fig. 4). The higher the deforestation rate in the province, the more effective the NNRs appeared to be in that province (linear regression, unmatched: $R^2 = 0.49$, $F_{1,24} = 23.44$, $p < 0.001$; matched: $R^2 = 0.71$, $F_{1,24} = 59.81$, $p < 0.001$) (Fig. 4). Hansen et al.'s Landsat data showed similar results; 24 of 26 provinces exhibited effectiveness ($p < 0.05$, paired t -test with fdr correction) with both approaches (unmatched: 23 of 26; matched: 20 of 26 provinces) (Supporting Information).

Discussion

Forest Cover and Loss and NFPP Effectiveness

Consistent with previous reports (Richardson 1990; Song & Zhang 2010; Hansen et al. 2013), most of the forest and woodland cover was located in China's northeast (Inner Mongolia, Heilongjiang, Jilin, and Liaoning), followed by the southwest (Yunnan, Sichuan, Tibet), and then the southeast (Guangxi, Guangdong, Fujian, Jiangxi, Hunan).

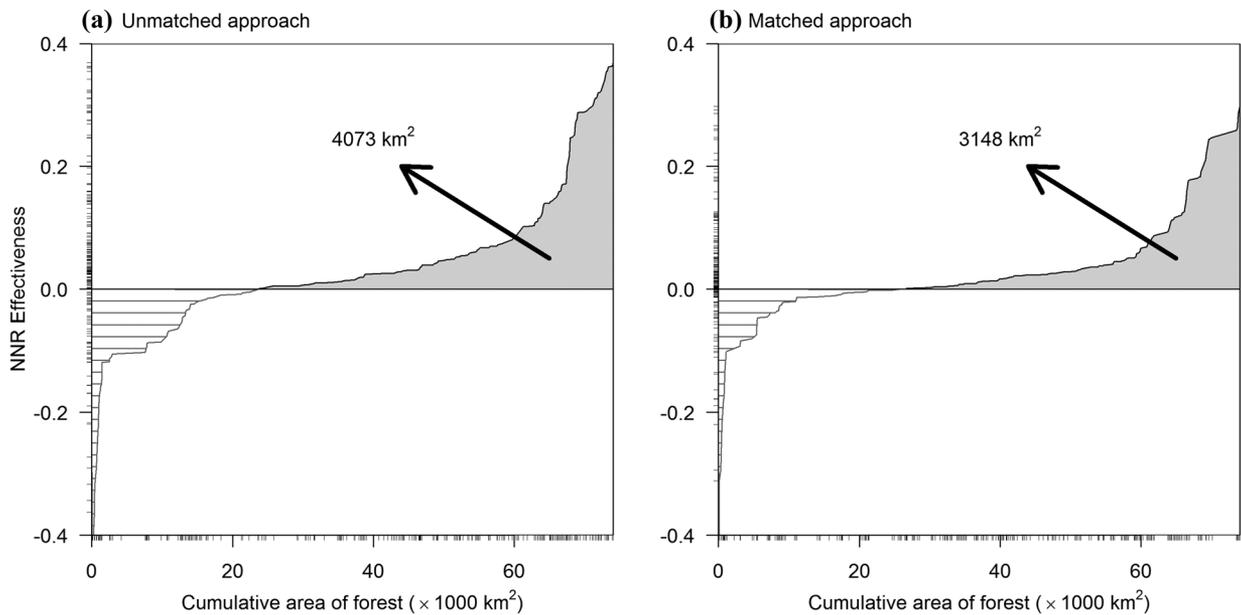


Figure 3. Effectiveness of NNRs in protecting forest cover in 2000–2010 as determined with (a) conventional unmatched approach and (b) covariate-matching approach (axis line demarcations: x-axis, each NNR's contribution to total forest cover; y-axis, each NNR's effectiveness). The NNRs are ordered from lowest (negative) to highest (positive) effectiveness..

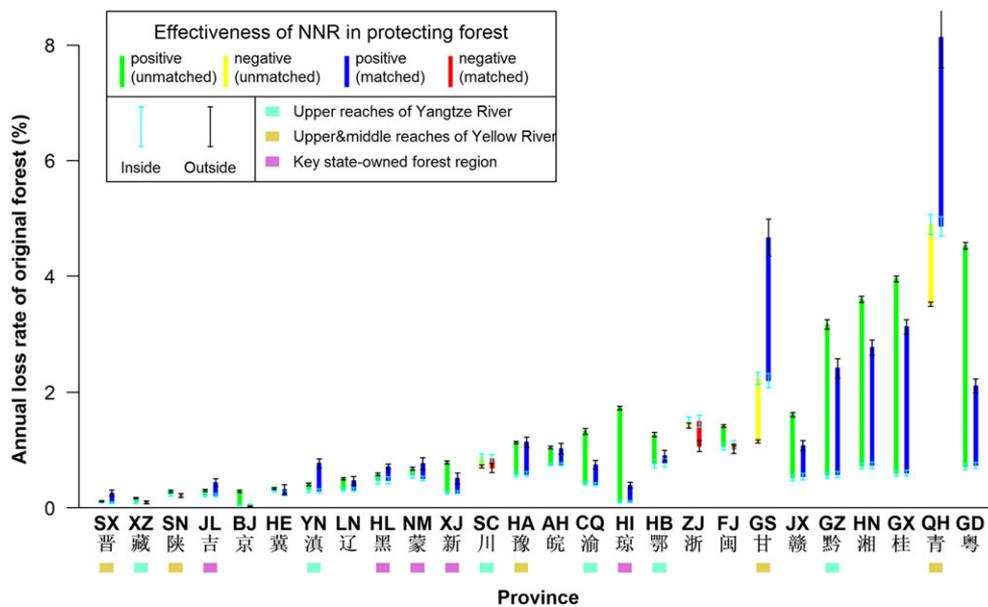


Figure 4. Effectiveness of NNRs in protecting forest cover in 2000–2010 by province. Provinces are aligned from left to right by each province's deforestation rate. Annual loss of forest cover is shown for conventional unmatched sampling and matched covariate sampling approaches. For blue and green bars, the deforestation rate inside the NNRs is lower than outside the NNRs. For red and yellow bars, the deforestation rate inside the NNRs is higher than outside the NNRs. Most provinces show a lower deforestation rate inside the NNRs. Scheme of colored rectangles on the x-axis follows that in Fig. 2's inset.

Although the loss of biodiversity and natural forests are global concerns, institutions for managing and conserving these resources mostly originate domestically, especially in large countries like China, which have

endogenously developed legal and political systems. During 2000–2010, we estimate that already extant, mostly natural forest cover declined from 12.3% to 10.9% of mainland China, and original forest and woodland cover

declined from 18.7% to 13.6%. From 2000 to 2010, this translates to a 1.05% annual loss rate and a half-life of 65 years for forest only and to a 2.84% annual loss rate and a 24-year half-life for forest and woodland.

Most of the narrow-sense deforestation (δ_{forest}) occurred in the 14 non-NFPP provinces (annual rate 2.07% in 2000–2010), especially in southeastern China (Figs. 1 & 2), while the annual rate across the 17 NFPP provinces was 3.3 times lower, at 0.62%. Moreover, within the NFPP provinces, most of the narrow-sense deforestation was concentrated in two provinces, Heilongjiang and Inner Mongolia in northeastern China (Fig. 2), which were designated in the NFPP as “key state-owned forest regions.” Logging was not as strictly banned in this region as in the watersheds of the Yangtze and Yellow Rivers.

Broad-sense deforestation ($\delta_{\text{forest+woodland}}$) was similarly higher in the non-NFPP provinces, especially in southeastern China (annual rate 4.26% in 2000–2010), than in the NFPP provinces (2.26%). However, two NFPP provinces, Yunnan and Sichuan, through which the Yangtze River passes and which house a high fraction of China’s biodiversity (Wu et al. 2011), also showed high levels of $\delta_{\text{forest+woodland}}$ (Fig. 2).

Although not a focus of our analysis, several studies suggest that an important driver of forest loss across all provinces is replacement by tree plantations (Li 2004; Li et al. 2007; Wang et al. 2007a; Song & Zhang 2010; Xu 2011), especially *Eucalyptus*, to meet high demand for wood products (Lin 2001; Tang 2005; Zhang et al. 2012). In Yunnan, Guangdong, and Hainan, which have tropical to sub-tropical climates, rubber plantations are also an important driver (Li et al. 2007). Northwestern Yunnan and western Sichuan have had increased pressure on forests from increases in tourism and living standards (Brandt et al. 2012). It also appears that permission was given to log some 1970s-era planted forests in Sichuan and Yunnan.

Provinces differ in many more ways than whether they were included in the NFPP, so we cannot unambiguously attribute low deforestation in the NFPP provinces to the success of that program. However, our estimates for 2000–2010 annual rates of broad- and narrow-sense deforestation in the NFPP provinces ($\delta_{\text{forest+woodland}} = 2.26\%$, $\delta_{\text{forest}} = 0.62\%$, respectively) approach and more than achieve the target of reducing NFPP-zone annual deforestation to 1.1% (Fig. 2).

In addition, Hansen et al.’s (2013) Landsat-based analysis of global forest cover (2000 to 2012) gives us further reason to believe that China more than achieved its NFPP goal. Hansen et al.’s estimates are consistent with ours in terms of forest cover in 2000 (this study: 1.765 million km², 40–100% tree cover; Hansen et al. [2013]: 1.702 million km², 26–100% tree cover) and the spatial distribution of cover and subsequent loss. However, Hansen et al. (2013) found a lower deforestation rate (0.51% annual rate for 2000–2012 for tree cover >75%) than

we did (1.05% for 2000–2010), which is likely explained by the smaller pixel sizes in Landsat images (30×30 m = 900 m²) relative to MODIS (231.7×231.7 m = 53685 m²). Partial deforestation in a MODIS pixel is sometimes scored as whole-pixel deforestation, leading to overestimates. Much of the deforestation in China captured by Hansen et al. was sub-MODIS pixel in size. Thus, Hansen et al.’s (2013) analysis suggests our analysis is conservative and that China therefore overachieved its NFPP deforestation reduction target for both forest and woodland ecotypes.

Whether the lost forest cover was natural or due to plantations does not change our conclusion regarding the drop in deforestation in NFPP provinces because we implicitly assumed that all lost forest was natural. If the lost forest cover had been mainly plantations, then the NFPP would have been even more effective than we determined.

Effectiveness of NNRs

The NNR designation has also successfully reduced deforestation in most provinces and in approximately two-thirds of NNRs (Figs. 3 & 4), but NNRs have not collectively prevented deforestation outright. Moreover, the low total avoided deforestation (estimated range 3148–4073 km², Fig. 3) derives from the simple fact that China’s NNR coverage is biased away from forest ecosystems (Fig. 1) (Joppa & Pfaff 2009; Wu et al. 2011).

However, our analysis of NNR effectiveness is conservative for two reasons. We did not separate natural (e.g., fire, insects) from anthropogenic causes of forest loss. Also, we only analyzed national-level reserves and had to ignore provincial, municipal, and county-level reserves due to missing polygon data. Thus, some of our outside-NNR pixels may have been in these lower-level reserves, which, if protected, would have reduced the inferred effectiveness of the NNRs.

The effectiveness of the NNRs varied across provinces (Fig. 4). An NNR that successfully protected forest cover inside its borders appeared to increase in effectiveness as the deforestation rate outside its borders increased. Thus, estimated effectiveness was greater in non-NFPP provinces, particularly in areas of concentrated deforestation (i.e., Guangdong, Hunan, and Guangxi) (Results, Fig. 4). We found that the deforestation rate inside NNRs was positively correlated with deforestation in the province as a whole (linear regression, unmatched: $R^2 = 0.49$, $F_{1,24} = 23.44$, $p < 0.001$; matched: $R^2 = 0.71$, $F_{1,24} = 59.81$, $p < 0.001$). We speculate that causality runs in the direction of generally laxer forest-protection governance at the provincial level (e.g., not being an NFPP province). This laxness may have led to lower levels of protection inside NNRs as well. The analysis of the effectiveness of NNRs with Hansen et al.’s (2013) Landsat data (Supporting Information) showed similar patterns as for

the MODIS data, though the MODIS data overestimated deforestation relative to the Landsat data. Both datasets demonstrated that the NNRs at the provincial level were successful at protecting forest cover. The two provinces that differed the most between datasets were Gansu and Qinghai because they had the greatest extent of small fragmented forests, which are better suited to the higher spatial-resolution data.

Our study provides the first assessment of China's two most important forest-protection policies. Since the introduction of the NFPP in 2000, the annual rate of forest loss has declined to, at most, a moderately low 1.05% across the country, but the annual forest and woodland loss rate is higher in non-NFPP and in two NFPP provinces, Sichuan and Yunnan, which are biodiversity hotspots in China. The analysis of finer spatial resolution Landsat data showed that use of MODIS data overestimate deforestation, but both datasets showed similar patterns of deforestation. Our results are consistent with many geographically focused analyses in China (Li 2004; Li et al. 2007; Wang et al. 2007a; Song & Zhang 2010; Xu 2011; Zhai et al. 2012) that report natural forests are being replaced by plantations, and it appears it is mostly woodland that is being replaced. The NFPP has been renewed for 2011–2020, and it will be instructive to continue monitoring its performance (SFA PRC 2000, 2010a).

The reason NNRs in China have not been comprehensively assessed earlier is because most nature reserves in China do not have published borders. Establishing a public database of all nature-reserve borders is a key conservation priority for China. Another priority is to establish or upgrade nature reserves in southern and eastern China, where coverage is clearly inadequate, deforestation rates are highest, and natural forests are quickly disappearing (Wu et al. 2011).

Our study contributes to the so far limited evidence base on protected-area effectiveness that has recently been reviewed by Joppa and Pfaff (2011) and Geldmann et al. (2013). We also found that protected areas prevent deforestation, but often with low effectiveness (Fig. 3). Also, most of the protected-area coverage in China is not of forest ecosystems. Little evidence exists anywhere that relates management variables to effectiveness, but our results suggest that province-level forest governance may be positively correlated with protected-area effectiveness. Determining if this link is causal is an important research direction.

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Supporting Information

Detailed methods (Appendix S1) and a high resolution version of Fig. 1 (Appendix S2) are available online. The authors are solely responsible for the content and functionality of these materials. Queries (other than the absence of material) should be directed to the corresponding author.

Literature Cited

- Andam KS, Ferraro PJ, Pfaff A, Sanchez-Azofeifa GA, Robalino JA. 2008. Measuring the effectiveness of protected area networks in reducing deforestation. *Proceedings of the National Academy of Sciences of the United States of America* **105**:16089–16094.
- Bartholome E, Belward AS. 2005. GLC2000: a new approach to global land cover mapping from Earth observation data. *International Journal of Remote Sensing* **26**:1959–1977.
- Brandt JS, Kuemmerle T, Li HM, Ren GP, Zhu JG, Radeloff VC. 2012. Using Landsat imagery to map forest change in southwest China in response to the national logging ban and ecotourism development. *Remote Sensing of Environment* **121**:358–369.
- Breiman L. 2001. Random forests. *Machine Learning* **45**:5–32.
- Chazdon RL. 2008. Beyond deforestation: Restoring forests and ecosystem services on degraded lands. *Science* **320**:1458–1460.
- Clark ML, Aide TM, Grau HR, Riner G. 2010. A scalable approach to mapping annual land cover at 250 m using MODIS time series data: a case study in the Dry Chaco ecoregion of South America. *Remote Sensing of Environment* **114**:2816–2832.
- Dorais A, Cardille J. 2011. Strategies for incorporating high-resolution Google Earth databases to guide and validate classifications: understanding deforestation in Borneo. *Remote Sensing* **3**:1157–1176.
- Economy EC. 2007. The great leap backward? The costs of China's environmental crisis. *Foreign Affairs* **86**:38–59.
- Gaveau DLA, Epting J, Lyne O, Linkie M, Kumara I, Kanninen M, Leader-Williams N. 2009. Evaluating whether protected areas reduce tropical deforestation in Sumatra. *Journal of Biogeography* **36**:2165–2175.
- Geldmann J, Barnes M, Coad L, Craigie ID, Hockings M, Burgess ND. 2013. Effectiveness of terrestrial protected areas in reducing habitat loss and population declines. *Biological Conservation* **161**:230–238.
- Hansen MC, et al. 2013. High-resolution global maps of 21st-century forest cover change. *Science* **342**:850–853.
- Hansen MC, Stehman SV, Potapov PV. 2010. Quantification of global gross forest cover loss. *Proceedings of the National Academy of Sciences of the United States of America* **107**:8650–8655.
- Joppa LN, Loarie SR, Pimm SL. 2008. On the protection of "protected areas." *Proceedings of the National Academy of Sciences of the United States of America* **105**:6673–6678.
- Joppa LN, Pfaff A. 2009. High and far: biases in the location of protected areas. *PLOS ONE* **4**(e8273) DOI: 10.1371/Journal.Pone.0008273.

- Joppa LN, Pfaff A. 2011. Global protected area impacts. *Proceedings of the Royal Society B: Biological Sciences* **278**:1633–1638.
- Kahn J, Yardley J. 2007. As China roars, pollution reaches deadly extremes. *New York Times*, 26 August, 2007.
- Li HM, Aide TM, Ma YX, Liu WJ, Cao M. 2007. Demand for rubber is causing the loss of high diversity rain forest in SW China. *Biodiversity and Conservation* **16**:1731–1745.
- Li S-C, Yang Q-Y. 2000. Socioeconomic factors determining China's deforestation rates. *Geographical Research (in Chinese with English abstract)* **19**:1–7.
- Li WH. 2004. Degradation and restoration of forest ecosystems in China. *Forest Ecology and Management* **201**:33–41.
- Liaw A, Wiener M. 2002. Classification and regression by randomForest. *R news* **2**:18–22.
- Lin Y. 2001. A review on ecological effects of *Eucalyptus* plantation in Guangdong province. *Forestry Science and Technology (in Chinese with English abstract)* **17**:32–36.
- Liu J, Ouyang Z, Pimm SL, Raven PH, Wang X, Miao H, Han N. 2003. Protecting China's biodiversity. *Science* **300**:1240–1241.
- Liu JG, Diamond J. 2005. China's environment in a globalizing world. *Nature* **435**:1179–1186.
- Liu JG, Li SX, Ouyang ZY, Tam C, Chen XD. 2008. Ecological and socioeconomic effects of China's policies for ecosystem services. *Proceedings of the National Academy of Sciences of the United States of America* **105**:9477–9482.
- Liu JG, Linderman M, Ouyang ZY, An L, Yang J, Zhang HM. 2001. Ecological degradation in protected areas: The case of Wolong Nature Reserve for giant pandas. *Science* **292**:98–101.
- MEP PRC. 2010. 2010 Report on the state of the environment in China. <http://jcs.mep.gov.cn/hjzl/zkgb/2010zkqb/> (in Chinese, last accessed October 22, 2013).
- MEP PRC. 2013. 2012 Report on the state of the environment in China. <http://www.mep.gov.cn/gkml/hbb/qt/201306/W020130606578292022739.pdf> (in Chinese, last accessed in October 22, 2013).
- Nagendra H. 2008. Do parks work? Impact of protected areas on land cover clearing. *Ambio* **37**:330–337.
- Nolte C, Agrawal A, Silvius KM, Soares BS. 2013. Governance regime and location influence avoided deforestation success of protected areas in the Brazilian Amazon. *Proceedings of the National Academy of Sciences of the United States of America* **110**:4956–4961.
- Perfecto I, Vandermeer J. 2010. The agroecological matrix as alternative to the land-sparing/agriculture intensification model. *Proceedings of the National Academy of Sciences of the United States of America* **107**:5786–5791.
- Richardson SD. 1990. *Forests and forestry in China: changing patterns of resource development*. Island Press, Washington D.C.
- Rudel TK. 2009. Tree farms: Driving forces and regional patterns in the global expansion of forest plantations. *Land Use Policy* **26**:545–550.
- SFA PRC. 2000. The implementation plan of the natural forest protection project in the key state-owned forest regions of Northeast China, Inner Mongolia, etc. and The implementation plan of the natural forest protection project in the upper reaches of the Yangtze River, and the upper and middle reaches of the Yellow River. State Forestry Administration PRC, Beijing. Available from http://www.ndrc.gov.cn/fzggz/fzgh/ghwb/115zxgh/200709/t20070927_163749.html (accessed December 2014) (in Chinese).
- SFA PRC. 2005. The sixth national forest resources inventory and the status of forest resources. (in Chinese with English abstract). *Green China* **2**:10–12.
- SFA PRC. 2010a. The phase II implementation plan of the natural forest protection project in the key state-owned forest regions of Northeast China, Inner Mongolia, etc. and The phase II implementation plan of the natural forest protection project in the upper reaches of the Yangtze River, and the upper and middle reaches of the Yellow River. State Forestry Administration PRC, Beijing. Available from <http://www.forestry.gov.cn/ZhuantiAction.do?dispatch=content&id=485662&name=trlbhgc> (accessed October 2013) (in Chinese).
- SFA PRC. 2010b. The seventh national forest resources inventory and the status of forest resources (in Chinese with English abstract). *Forest Resource Management* **1**:1–8.
- Solano R, Didan K, Jacobson A. 2010. MODIS vegetation index user's guide (MOD13 series). Version 2.00, http://vip.arizona.edu/documents/MODIS/MODIS_VI_UsersGuide_01_2012.pdf (accessed 26 June 2013).
- Song C, Zhang Y. 2010. Forest cover in China from 1949 to 2006. Pages 341–356 in *Reforestation landscapes*. Springer, The Netherlands.
- Tang M-S. 2005. Speeding the utilization of fast-growing plantation to promote development of forestry industry in Hunan. *China Forest Products Industry* **32**:48–50.
- Wang G, Innes JL, Lei J, Dai S, Wu SW. 2007a. China's forestry reforms. *Science* **318**:1556–1557.
- Wang S, Chen JM, Ju WM, Feng X, Chen M, Chen P, Yu G. 2007b. Carbon sinks and sources in China's forests during 1901–2001. *Journal of Environmental Management* **85**:524–537.
- Wang W, Pechacek P, Zhang MX, Xiao NW, Zhu JG, Li JS. 2013. Effectiveness of nature reserve system for conserving tropical forests: a statistical evaluation of Hainan island, China. *PLOS ONE* **8** (e57561) DOI: 10.1371/journal.pone.0057561.
- Wittemyer G, Elsen P, Bean WT, Burton ACO, Brashares JS. 2008. Accelerated human population growth at protected area edges. *Science* **321**:123–126.
- World Bank. 2001a. *China: air, land, and water*. World Bank, Washington D.C.
- World Bank. 2001b. *Trading economics*. Available from <http://www.tradingeconomics.com/china/forest-area-percent-of-land-area-wb-data.html> (accessed September 2013).
- Wu RD, Zhang S, Yu DW, Zhao P, Li XH, Wang LZ, Yu Q, Ma J, Chen A, Long YC. 2011. Effectiveness of China's nature reserves in representing ecological diversity. *Frontiers in Ecology and the Environment* **9**:383–389.
- Xu JC. 2011. China's new forests aren't as green as they seem. *Nature* **477**:370–370.
- Zhai D-L, Xu J-C, Dai Z-C, Cannon CH, Grumbine R. 2012. Increasing tree cover while losing diverse natural forests in tropical Hainan, China. *Regional Environmental Change* **14**:611–621.
- Zhang J-M, Gao G, Chen Y. 2001. Climate background of flooding and waterlogging and disaster inducing factors of the Yangtze valley. *Resource Science (in Chinese with English Abstract)* **23**:73–77.
- Zhang J, Wei X, Fu F, Luo S. 2012. Survey and economic benefit evaluation on fast-growing and high-yielding *Eucalyptus* *SPP* plantation in Guangxi. *Forestry Economics (in Chinese with English abstract)* **9**:34–37.
- Zhang PC, Shao GF, Zhao G, LeMaster DC, Parker GR, Dunning JB, Li QL. 2000. China's forest policy for the 21st century. *Science* **288**:2135–2136.
- Zong YQ, Chen XQ. 2000. The 1998 flood on the Yangtze, China. *Natural Hazards* **22**:165–184.