Potential Effects of Ongoing and Proposed Hydropower Development on Terrestrial Biological Diversity in the Indian Himalaya

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Abstract: *Indian Himalayan basins are earmarked for widespread dam building, but aggregate effects of these dams on terrestrial ecosystems are unknown. We mapped distribution of 292 dams (under construction and proposed) and projected effects of these dams on terrestrial ecosystems under different scenarios of land-cover loss. We analyzed land-cover data of the Himalayan valleys, where dams are located. We estimated dam density on fifth- through seventh-order rivers and compared these estimates with current global figures. We used a species–area relation model (SAR) to predict short- and long-term species extinctions driven by deforestation. We used scatter plots and correlation studies to analyze distribution patterns of species and dams and to reveal potential overlap between species-rich areas and dam sites. We investigated effects of disturbance on community structure of undisturbed forests. Nearly 90% of Indian Himalayan valleys would be affected by dam building and 27% of these dams would affect dense forests. Our model projected that 54,117 ha of forests would be submerged and 114,361 ha would be damaged by dam-related activities. A dam density of 0.3247/1000 km^2 would be nearly 62 times greater than current average global figures; the average of 1 dam for every 32 km of river channel would be 1.5 times higher than figures reported for U.S. rivers. Our results show that most dams would be located in species-rich areas of the Himalaya. The SAR model projected that by 2025, deforestation due to dam building would likely result in extinction of 22 angiosperm and 7 vertebrate taxa. Disturbance due to dam building would likely reduce tree species richness by 35%, tree density by 42%, and tree basal cover by 30% in dense forests. These results, combined with relatively weak national environmental impact assessment and implementation, point toward significant loss of species if all proposed dams in the Indian Himalaya are constructed.*

Keywords: dams, land-cover change, land-use change, species extinction, species richness

Efectos Potenciales del Desarrollo Hidroeléctrico Actual y Propuesto sobre la Diversidad Biológica Terrestre en el Himalaya Hindú

Resumen. *Las cuencas del Himalaya Hindú están destinadas para la construcción extensiva de presas, pero se desconocen los efectos agregados de estas presas sobre los ecosistemas terrestres. Mapeamos la distribución de 292 presas (en construcción y propuestas) y los efectos proyectados de estas presas sobre los ecosistemas terrestres bajo diferentes escenarios de pérdida de cobertura de suelo. Analizamos datos de cobertura de suelo de los valles del Himalaya, donde se localizan las presas. Estimamos la densidad de presas en ríos de quinto a séptimo orden y comparamos estas estimaciones con cifras globales actuales. Utilizamos un modelos*

de relación especies-área (REA) para predecir extinciones de especies a corto y largo plazo provocadas por la deforestación. Usamos gráficas de dispersión y estudios de correlación para analizar los patrones de distribución de especies y presas y para revelar el traslape potencial entre áreas ricas en especies y los sitios de las presas. Investigamos los efectos de la perturbación sobre la estructura de la comunidad de bosques no perturbados. Casi 90% de los valles del Himalaya Hindú pudiera ser afectado por la construcción de presas y 27% de estas presas podría afectar bosques densos. Nuestro modelo proyectó que 54,117 ha de bosques quedarían sumergidas y 114,361 ha serían dañadas por actividades relacionadas con las presas. Una densidad de presas de 0.3247/1000 km² sería casi 62 veces mayor que las cifras globales promedio actuales; el promedio de 1 presa por cada 32 km de río sería 1.5 veces mayor que la cifra registrada en ríos de E.U.A. Nuestros resultados muestran que la mayoría de las presas estaría localizada en áreas ricas en especies del Himalaya. El modelo REA proyectó que, en 2025, la deforestación debido a la construcción de presas probablemente resultaría en la extinción de 22 taxa de angiospermas y 7 de vertebrados. La perturbación debido a la construcción de presas probablemente reduciría la riqueza de especies de árboles en 35%, la densidad de árboles en 42% y la cobertura basal de árboles en 30% en los bosques densos. Estos resultados, combinados con una evaluación e implementación de impacto ambiental relativamente débil, apuntan hacia una pérdida significativa de especies si son construidas todas las presas propuestas en el Himalaya Hindú.

Palabras Clave: cambio en el uso de suelo, cambio en la cobertura de suelo, extinción de especies, presas, riqueza de especies

Introduction

Humans have been damming rivers for thousands of years, but during the second half of the 20th century, the number of rivers regulated for hydropower and irrigation increased substantially. There were 5000 large dams worldwide in 1950. By 2000, this number had increased to 45,000 (Khagram 2004). In the early years of this century, exponential growth of dam building ebbed worldwide due to technical, financial, and social and political reasons, but the number of dams in developing countries, particularly India and China, is rising (Pandit 2009; Grumbine & Xu 2011). In 2003, to meet a projected doubling of electricity demand by 2020, the Government of India (GOI) announced an ambitious plan to generate 50,000 MW (annual average electricity consumption of 400–900 households in the United States equals 1 MW) through the development of new hydropower infrastructure (GOI 2008). This would entail construction of 292 new dams to more than double India's existing capacity to generate electricity and add (in <15 years) new power equivalent to over half of all that currently exists in the United States (Dharmadhikary 2008).

Results of studies carried out in the developed countries in the northern hemisphere show river regulation is the most substantial and widespread human effect on riverine ecosystems (Dynesius & Nilsson 1994). Specific effects range from changes in river geomorphology and hydrology (Brandt 2000) to impairment of the ecological integrity of rivers through the extirpation of species and loss of ecosystem services (Richter et al. 2003). Altered flow regimes due to river regulation often result in the destruction and fragmentation of riverine and riparian ecosystems and extirpation of fishes (Lovett 1999), other freshwater fauna (Armitage et al. 1987), crocodiles (Dudgeon 2000), molluscs (Kowalewski et al. 2000), mayflies (Malmqvist & Englund 1996), benthic biota (Ward 1976), and riparian vegetation (Nilsson et al. 1997). Damming rivers changes downstream ecological processes and sets in motion complex chain reactions that transform floodplain vegetation dynamics (Wieringa & Morton 1996). Similar studies have not been conducted in Asia (Dudgeon 2000), and effects of river regulation on terrestrial and downstream riparian ecosystems in India remain largely unknown.

India has some of the densest human populations in the world and the GOI's numerous dam proposals would affect people. But little is known about project-specific effects, and no one has attempted to calculate, even for one river basin, the cumulative effects of multiple, closely spaced dams (but see CISMHE 2007). Civil societies in India are urging the GOI to improve assessment of the effects of dams on local communities. But federal regulatory mechanisms, such as the environmental impact assessment (EIA) process, have proven inadequate even for single dam projects (Nandimath 2009). On paper, there are robust GOI environmental impact policies for hydropower project appraisal, but their implementation remains uncertain. The law, for example, requires assessment of effects on biological diversity, including rare and endangered species and protected areas, but few projects have ever been rejected on the basis of these concerns (CSE 2011). Given this history and the scale of proposed hydropower development, it is doubtful that policies as they are currently implemented can adequately address up to 300 new proposals.

We reviewed proposed dam construction in the Indian Himalaya to examine land-cover change in regions where dams are being or will be built; predict species losses across taxonomic groups; quantify the effects of dam building on forests; and briefly review GOI's EIA
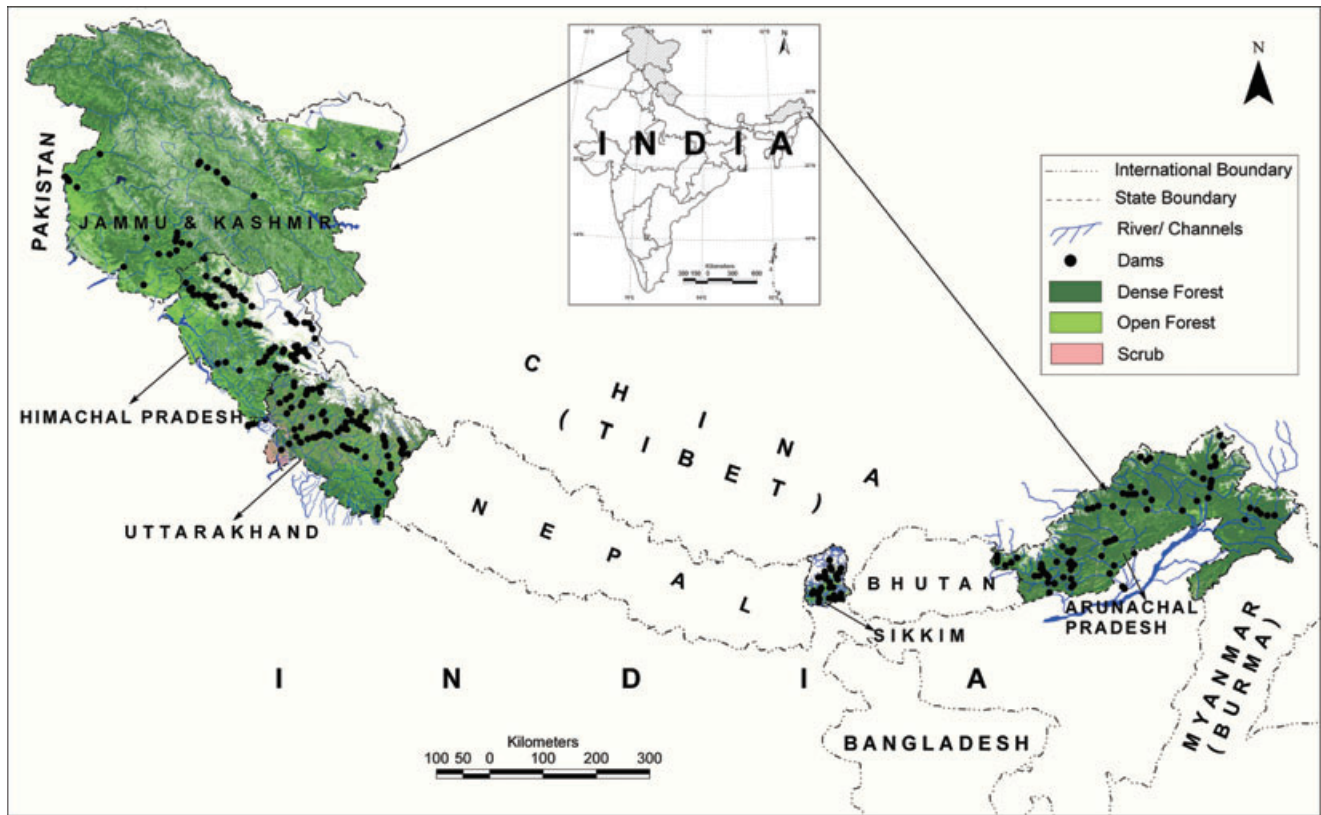
Figure 1. Distribution and density of dams, forest cover, and rivers across the Indian Himalaya.

policies and make suggestions for mitigating the adverse effects of dams.

Methods

Study Area and Data Sources

We considered all 3 major river basins of the Indian Himalaya (Ganga, 1,086,000 km²; Indus, 930,000 km; Brahmaputra, 580,000 km²) in which dams are being planned (Fig. 1). The Brahmaputra has the highest mean annual water discharge (629.05 km³/yr), followed by the Ganga (525.02 km³/yr) and the Indus (73.31 km³/yr) (Kumar et al. 2005). These river basins have a cumulative hydropower potential of over 100,000 MW (CWC 1992).

We obtained names, locations (elevation), and installed capacities (i.e., megawatts) of 292 proposed dams and detailed data on 113 of these dams from GOI agencies (CEA 2004) (see Supporting Information). For the remaining 179 dams, we obtained these data from other sources (Supporting Information). We procured data on building of dams in forests from completed EIA reports on 32 dams (Supporting Information). Our data included size, height, water-storage and run-of-the-river design, and details of dam-building activities in forested or nonforested areas (Supporting Information).

Spatial Analyses

We used ArcGIS 9.1 software (ESRI, Redmond, California) depicting geographic locations of states, river channels, and river valleys to prepare a georeferenced base map of the Indian Himalaya from Survey of India topographic maps at 1:50,000 or 1:250,000 scales. River valleys were demarcated following major watershed boundaries (not shown here). We classified climatic zones in these valleys as tropical or subtropical southern plains (≤1000 m), temperate (1000–3000 m), and subalpine and alpine (>3000 m) (Grytnes & Vetaas 2002). We used the distance-measuring tool in ArcGIS 9.1 to calculate the length of fifth- to seventh-order river channels. We added dams to the base map as a distinct layer.

Once the spatial data layers were completed, we used remotely sensed data from Landsat ETM+ (Arunachal Pradesh, 2001, 2005, 2006; Sikkim, 2005; Uttarakhand, Himachal Pradesh, and Jammu and Kashmir, 2000, 2001) (30-m resolution) to delineate forest and nonforest land cover with Erdas Imagine 9.1 software (Intergraph, Madison, Alabama, U.S.A.). We converted the satellite data to a false-color composite (FCC) image (bands 2, 3, and 4) and extracted the area of interest with Erdas Imagine 9.1 software. We classified the FCC with supervised and unsupervised procedures (Jha et al. 2000). Forest cover was classified as dense, canopy cover >40%; open, canopy cover between 10% and 40%; and degraded, forest or

scrub with <10% canopy cover (FSI 2005). We considered dense forests undisturbed and open and degraded forests disturbed land-cover types.

We overlaid the land-cover images on the base map to visualize dam locations on the basis of forest cover classes (Fig. 1). The remotely sensed data were preprocessed and therefore did not require geometric and radiometric corrections. We reduced errors in the interpretation of satellite images and their classification to delineate forest and nonforest land cover (Congalton 2001) by sourcing cloud-free and georeferenced data from a single satellite and through maximum ground truthing. Ground truthing to validate land-cover types was carried out by surveying land-cover classes in the selected areas of river basins earmarked for dam building. We used a global positioning system (GPS) (GIS-GS5 with ArcPad version 6 software [Leica Geosystems, Switzerland]) to corroborate the land-cover types in the field with those of the classified remote sensing images by matching their geographic coordinates. We followed standard protocols to classify land cover (Joshi et al. 2001). We did not estimate spatial extents of different land-cover classes; rather, we used published information on forest cover, background deforestation (deforestation due to expansion of agriculture, human settlement, development of infrastructure, logging) rates (Pandit et al. 2007), and projected remaining forest cover classes after deforestation due to dam building.

Geographic Distribution of Dams

We analyzed the spatial distribution of dams to locate dams in different valleys and to project dam density, land-cover types affected by dam building across elevational gradients, extent of land-cover change driven by dam building, and loss of land cover assuming all planned dams were built. We compiled a list of proposed and under-construction dams and stating for each installed capacity, elevation, and land-cover type around the dam. From the composite overlay map, we collated information on the number of dams in each valley, dam density/1000 km^2 of basin area, average number of dams per kilometer of river channel, and number of dams in different land-cover classes and climatic zones. To analyze current average dam density per 1000 km^2, we downloaded data on 23 global river systems from Northwest Alliance for Computation Science & Engineering (NACSE 2011). We designated conversion of forests for dam building as loss of land cover due to intense human use and loss of natural values. Data on land area submerged under reservoirs were available for 113 dams (CEA 2004), but data on the area of forest converted for dam building was available for only 32 projects (Supporting Information). From the data on the 32 dams, we calculated average forest area used per megawatt hydroelectricity generated to project forest lost due to submergence and

to other dam-building activities. These activities include infrastructure building, mining, muck dumping, tunneling, and adits, which cumulatively can result in land-cover losses that have effects similar to that of submergence. We compared average land submergence for 113 dams (0.78 ha/MW) (CEA 2004) with our projections of land-cover loss for 32 dams (0.53 ha/MW) and found that our estimates were conservative (Supporting Information). The average forest submerged per megawatt and diverted for other dam-building activities was scaled for the projected power generation of 102,108 MW from 284 of 292 dams (8 dams are located in nonforested areas).

Species-Rich Zones and Dams

To estimate potential effects of dams on species, we plotted species richness across various taxonomic groups and the distribution of dams against elevational gradients and compared the resulting patterns. We used published data on the distribution and elevational ranges of angiosperms, mammals, birds, fishes, and butterflies to interpolate species' presence between maximum and minimum elevations (Supporting Information). We divided the Indian Himalayan elevational gradient (from 300 m, lower montane limit, to 4700 m, beyond which no dam is proposed) into 44 equal horizontal bands of 100-m elevational range. We assumed no species had an elevational distribution range of <100 m and that a species was represented at all elevations between its minimum and maximum elevational records (Grytnes & Vetaas 2002). This elevational species distribution pattern represents an estimate of the gamma diversity (i.e., total richness of an entire horizontal elevational band) of the taxonomic groups we analyzed (Lomolino 2001). We used scatter plots fitted with Friedman's supersmoother function (a nonparametric curve fit) to analyze patterns of distribution of species and dams on the basis of elevational gradient. Analyses were conducted with Spotfire S+ 8.1.1 software (TIBCO, Palo Alto, California, U.S.A.). We used Pearson's correlation coefficient (Spotfire S+ 8.1.1) to test the strength and significance of the correlation between the number of dams and species richness.

Land-Cover Change

In the Indian Himalaya, background deforestation due to multiple land-cover changes has resulted in species extinctions across various taxonomic groups (Pandit et al. 2007). Dam building is expected to further increase deforestation rates, so we estimated the extent of species loss driven by deforestation due to dam-building activities alone and in combination with background deforestation. To make new projections of forest cover in 2025 and 2100, we used known forest cover and deforestation rates in the Indian Himalaya (Pandit et al. 2007). We then

added our projections of forest loss due to dam-building activities on the basis of 2 scenarios: dams built only in already-degraded forests and dams built haphazardly across the landscape including in dense forests. We predicted the loss of angiosperm, mammal, bird, fish, reptile, and amphibian species on the basis of this projected deforestation data with a species–area relation (SAR) model (May & Stumpf 2000) ($S = cA^z$, where S is the ratio of contemporary to original species composition; A is the ratio of present to original habitat area [forest area of the study region], and c and z are constants [$z = 0.25$]). We examined projections of species extinction on the basis of z values ranging from 0.25 to 0.35. These z values are reported to be typical for mountain ecosystems (Pereira & Daily 2006). Short-term projections of species extinctions were made up to 2025 and long-term projections were made to 2100.

Some researchers question the linear relation between species richness and area (Lomolino 2000) because the SAR results of some studies are significantly affected by sampling design, spatial scale, and the types of organisms or habitats assessed (Drakare et al. 2006). Others, however, warn about underestimating its value (Koh et al. 2010; He & Hubbell 2011). Other models, such as the endemic SAR, have proven less reliable than SAR (Ulrich 2005). Given this debate and following Lewis (2006), who states that the power function (z) is often the best-fitting relation between species number and area, we used a conservative z value of 0.25 to derive extinction estimates (see Pereira & Daily 2006).

To quantify the effect of disturbance on tree community structure in dense forests, we measured tree species composition, species richness, density, and basal cover at 14 sites around proposed dams across the region. We analyzed whether differences in these variables might be due to regional variations or changes in land cover in disturbed and undisturbed forests. We considered only the tree species because of their dominance in the forest ecosystems. We selected study sites randomly within a 10-km² radius of proposed dams. Each site had undisturbed forest (control) and disturbed forest. We laid belt transects of 1–1.5 km × 10 m across each site. Each belt transect was subdivided into 10–15 quadrats of 10 m × 10 m and a species area curve was plotted. To ensure adequate sampling, we plotted species accumulation curves for all the sampling sites until curves reached a clear asymptote, which suggests no new species are being added. We quantitatively analyzed tree species richness and density and total basal cover following standard methods (Sagar et al. 2003). We tested the significance of differences in the studied variables between undisturbed and disturbed forests with 2-way analysis of variance with land use and land-cover type (disturbed or undisturbed forest) and region as fixed effects and land cover and region as interaction factors. This analysis was carried out in TIBCO Spotfire S$^+$ software (version 8.1.1).

Results

Geographic Distribution of Dams

There were 109 dams in the Brahmaputra, 89 in the Ganga, and 94 in the Indus River basins (Supporting Information). Average dam density across the Himalaya was 1.6120 dams/1000 km². Sikkim had the highest density (4/1000 km²), followed by Uttarakhand and Himachal Pradesh (both 1.5/1000 km²) (Table 1). If all dams were built, the Indian Himalayan river basins would have an average dam density of 0.3247/1000 km² (current global average is 0.0053/1000 km²) (Table 1). Dam densities in the Brahmaputra (0.5825/1000 km²), the Indus (0.2895/1000 km²), and the Ganga (0.1022/1000 km²) basins would be 110, 55, and 19 times higher, respectively, than the current global average.

Out of 32 major river valleys, 28 would be affected by dam building and nearly 90% of the dams would be located between the subtropical and temperate zones (Supporting Information). On average if all dams were built there would be one dam for every 32 km of fifth- to seventh-order river channel in the Indian Himalaya. The Ganga basin would have the highest number of dams (1/18 km of river channel dammed), followed by the Brahmaputra (1/35 km) and the Indus (1/36 km). Temperate regions would have the highest number of dams (52%), followed by tropical and subtropical (36%) and alpine regions (12%) (Supporting Information).

Land-Cover Change and Species Losses

In scenario 1 (if dams are built only in already-degraded forests), total forest affected was 51,001 ha excluding dense forests. In scenario 2 (if dams are built haphazardly across the landscape including in dense forests), forest lost to dam-building activities was 114,361 ha, including 63,360 ha of dense forests (Table 2). At current deforestation rates combined with loss of forest cover due to dam-related activities, total forest cover in the Indian Himalaya in 2025 was reduced by 0.32% and 0.73%, respectively (of 1970 baseline value) (Supporting Information).

Species richness of angiosperms, birds, and butterflies peaked around 600–1600 m (Fig. 2). This pattern was common to all taxonomic groups except fishes, which peaked around 500–600 m and had a second, minor peak between 1300 and 1500 m, and mammals, which exhibited a uniform distribution throughout the elevational gradients. Maxima of dams and species richness clearly overlapped (Fig. 2). For example, Sikkim, the most species-rich region of India (CISMHE 2007), would have the highest dam density in the world. There was a significant positive correlation between number of dams and species richness of angiosperms ($r = 0.846$; $p < 0.01$), birds ($r = 0.740$; $p < 0.01$), fishes ($r = 0.800$; $p < 0.01$), and butterflies ($r = 0.735$; $p < 0.01$). For mammals,

Table 1. Distribution and density of dams in the Indian Himalayan states and river basins and current density of dams in the major river basins of the world.

State/Basin	No. of dams	Geographic area (km^2)	Dam density (dams/km^2 of area of the state/basin)	Dam density (dams/1000 km^2 of area of the state/basin)
Arunachal Pradesh	80	83,743	0.00096	0.9600
Sikkim	29	7,096	0.00400	4.0000
Jammu & Kashmir	23	222,236	0.00010	0.1000
Himachal Pradesh	81	55,673	0.00150	1.5000
Uttarakhand	79	53,484	0.00150	1.5000
Himalayan States	292	422,232	0.00161	1.6120
Ganga	89	861,452	0.00010	0.1022
Indus	94	321,290	0.00029	0.2895
Brahmaputra	109	194,413	0.00056	0.5825
Himalayan Basins	292	1,377,155	0.00032	0.3247
Global basins*	194	36,591,693	0.00001*	0.0053*

On the basis of 23 major basins distributed across the 7 continents (NACSE 2011).

however, the correlation was not significant ($r = 0.293$; $p > 0.05$).

Projected extinction rates across taxonomic groups varied markedly depending on the specific species-area exponent (z) value used (Supporting Information). The lowest estimates of extinction across species groups had z values of 0.25 under both scenarios. For $z = 0.25$, 7.25% of angiosperm taxa and 7.27–7.62% of vertebrate taxa in the study area were extinct by 2025 due to forest loss. The highest extinction rates occurred when $z = 0.35$, in which case 10% of angiosperm and vertebrate taxa were extinct by 2025 (Supporting Information). Under the conservative SAR model in scenario 1, over the next 13 years, dam-building activity alone, if carried out in already-degraded forests, was predicted to lead to the extinction of 10 angiosperm and 3 vertebrate species. In scenario 2, haphazard dam building resulted in the loss of 114, 361 ha of forests (including 63,360 ha of dense forests) and in species extinctions doubling over the same period (Fig. 3a). By 2100 extinction projections under conservative SAR estimates indicated the potential loss of 1505 angiosperms and 274 vertebrates driven by background deforestation and dam building combined (Fig. 3b). We have been cautious with these projections. Our estimates of forest loss from dam building are lower than those projected by the GOI and we selected the most conservative z value (0.25) from the range of values recommended for mountain regions and matrix habitats.

Disturbed forests had 35% lower tree species richness, 42% lower tree density, and 30% lower tree basal cover compared with undisturbed forests (Fig. 4). Species richness differed significantly between disturbed and undisturbed forests ($F_{1,10} = 37.57$; $p < 0.001$). However, species richness did not differ significantly by region ($F_{1,10} = 0.02$; $p > 0.88$ and $F_{1,10} = 0.07$; $p > 0.79$). Density and tree basal cover differed significantly between disturbed and undisturbed forests ($F_{1,10} = 20.69$; $p < 0.001$ and $F_{1,10} = 18.15$; $p < 0.002$). Regional and inter-

action factors did not significantly affect density ($F_{1,10} = 0.23$; $p > 0.64$ and $F_{1,10} = 0.03$; $p > 0.86$) and tree basal cover ($F_{1,10} = 1.78$; $p > 0.21$ and $F_{1,10} = 1.02$; $p > 0.34$) of disturbed and undisturbed forests (Fig. 4).

Discussion

Distribution of Dams

Our results provide the first broad portrait of the effects of proposed dam building in the Indian Himalaya on terrestrial ecosystems and their biological diversity. Our estimates of dam densities did not include existing dams; we considered only projects under construction and proposed projects for which feasibility studies have been carried out by the GOI. If all proposed 292 dams are constructed, on the basis of the current global number of dams, the region will have the highest density of dams in the world. The average of 1 dam/32 km of fifth- to seventh-order river channel would be 1.5 times greater than figures reported from the United States, where the results of a study of the effects of dam density showed continental-scale effects favoring spread of cosmopolitan, non-native species at the expense of native biota (Poff et al. 2007). A disproportionately high percentage (90%) of dams would be concentrated in species-rich subtropical and temperate zones in the Indian Himalaya. Yet at present, due to limited studies and little certainty about the likelihood of all projects being built, it is difficult to quantify precisely the full extent of ecological changes that may result from proposed dam building.

Terrestrial Species Losses

We found a clear overlap between areas with maximum numbers of dams and species in the Indian Himalaya. More specifically, our results show that the projected forest loss from submergence and dam-building activities would have adverse effects on the persistence of

Table 2. Estimates of total forest and nonforest submerged and diverted by dams under different dam-building scenarios in the Indian Himalaya[a].

State	No. of dams	Hydroelectric capacity (MW)[b]	Reported land submergence (ba)[c]	Projected nonforest land submergence (ba)[d]	Projected forest loss[d]			
					dense forest loss (ba)	submergence (ba) [1]	other activities (ba) [2]	total forest loss (ba) [1 + 2]
Arunachal Pradesh	42	27,293	17,026	18,286	7,642	14,465	16,103	30,568
Sikkim	10	1,469	442	984	411	779	867	1,645
Uttarakhand	33	5,282	1,134	3,539	1,479	2,799	3,116	5,916
Himachal Pradesh	15	3,328	819	2,230	932	1,764	1,964	3,727
Jammu & Kashmir	13	2,675	11,900	1,792	749	1,418	1,578	2,996
Total (Himalaya)	113	40,047	31,321	26,831	11,213	21,225	23,628	44,853
Land cover loss dense forests (>40% canopy cover)	80	56,571	–	37,904	15,840	29,983	33,377	63,360
Nonforest land	8	607	–	406	0	0	0	0
Dam-building scenario								
1[e]	204	45,537	–	30,510	12,750	24,135	26,867	51,001
2[f]	284	1,02,108	–	68,412	28,590	54,117	60,244	1,14,361

[a]See methodology section and Supporting Information for computational details.
[b]This is installed capacity, which refers to maximum amount of electricity that a power plant can produce at any given point in time.
[c]Land submergence from 113 dams; data sourced from Central Electricity Authority (2004) (–, data not available).
[d]Our estimates on the basis of data from 32 dams (for sources see Supporting Information) under 4 rates of conversion of nonforest land and forest use per megawatt hydroelectricity generated to project forest lost due to submergence and to other dam-building activities: nonforest land submergence, 0.67 ba/MW; dense forest loss,0.28 ba/MW; forest areas submerged, 0.53 ba/MW; and forests loss due to other dam-building activities, 0.59 ba/MW.
[e]Dam building restricted to already degraded forests.
[f]Dam-building activities carried out baphazardly across the Himalayan landscapes, including in dense forests.
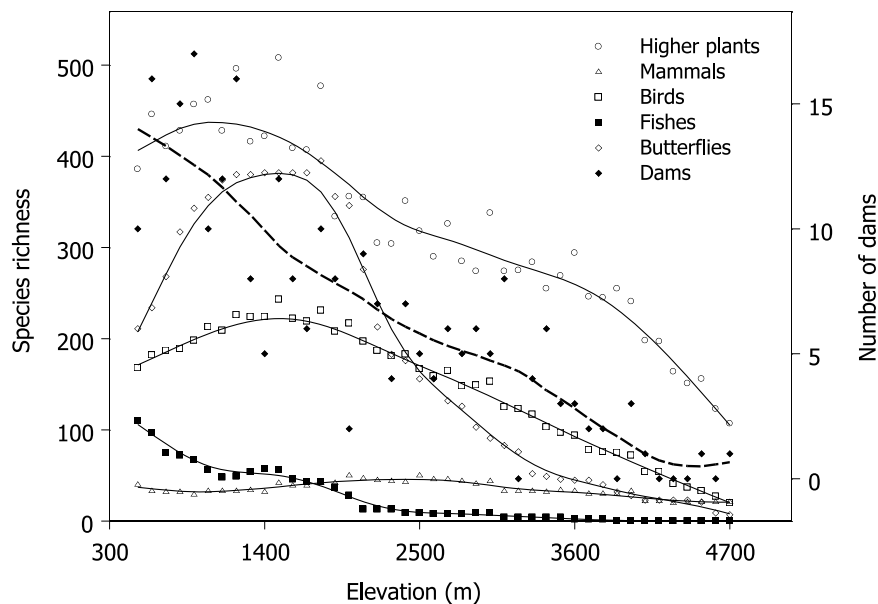
Figure 2. Species-richness of different taxonomic groups by elevation and relation between number of dams (dashed line) and elevation across the Indian Himalaya (fitted lines, constructed with Freidman's supersmoother function and meant only as a guide).

species across taxonomic groups. Submergence would result in direct elimination of species, but a high density of dams and associated construction activities would also change land cover and thus be detrimental to species survival. Forest loss and fragmentation negatively affect species diversity, and when forest loss and fragmentation

are associated with the creation of dams and reservoirs, the altered ecosystems can have sudden species losses (Terborgh 1974; Terborgh et al. 2001; Laurance et al. 2002). Although various taxonomic groups may respond differently to forest fragmentation and degradation (Irwin et al. 2010), our results concur with observations
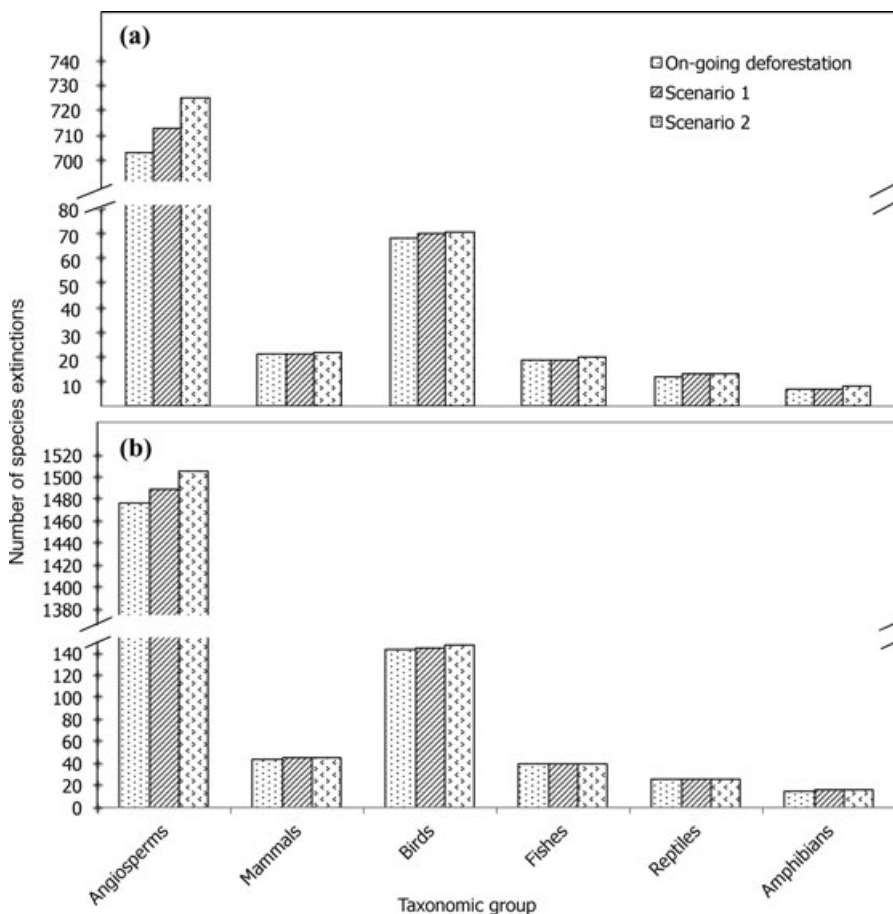

Figure 3. Projected number of species extinctions within taxonomic groups due to ongoing deforestation and forest loss due to dam building in the Indian Himalaya for species–area relations with a z value of 0.25 in (a) 2025 and (b) 2100 (scenario 1, dams built only in already-degraded forests; scenario 2, dams built haphazardly across the landscape including in dense forests). Predictions of extinctions are based on forest area data from Pandit et al. (2007).
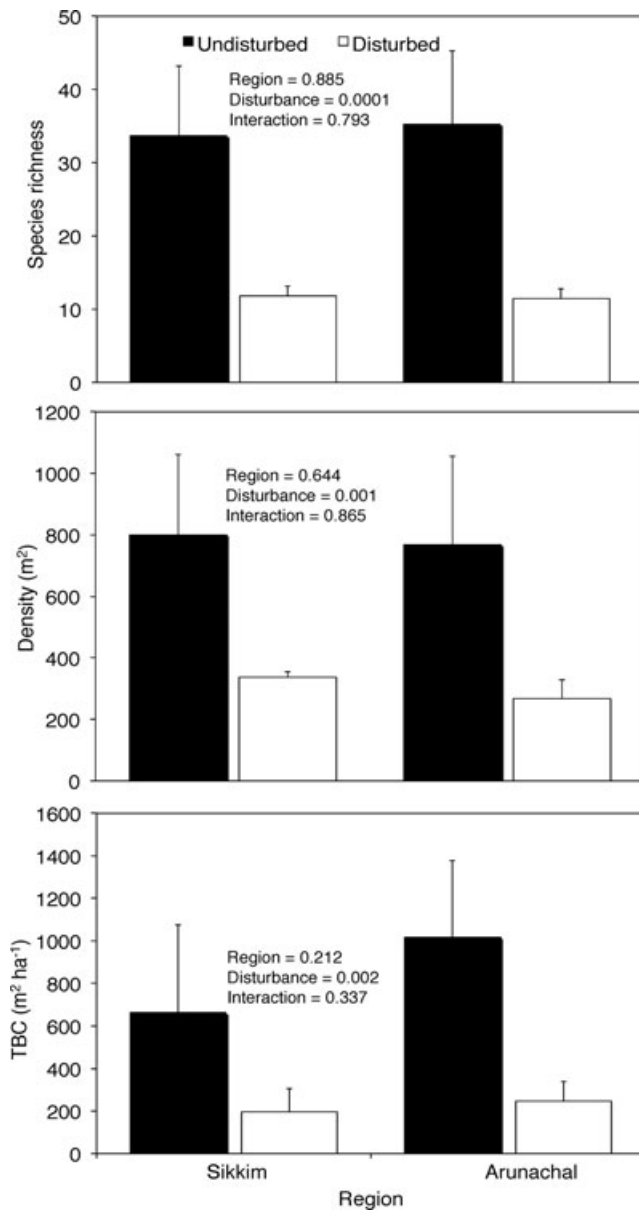
*Figure 4. Differences between tree species richness, density, and total basal cover (TBC) in undisturbed and disturbed forests in the Indian Himalaya (*n = 14; *numbers above bars,* p *values from significance tests; error bars, standard deviation of the mean).*

that show disturbance leads to decreases in abundance, species richness, and density and basal cover of trees and negative effects on community structure (Trzcinski et al. 1999; Fahrig 2003; Vellend et al. 2006).

Of course our species-extinction projections are subject to errors, which include over- or underestimation of species richness. We have already mentioned debates surrounding SAR models, but in addition, deforestation rates can be miscalculated on the basis of land-cover change analyses. However, considering the paucity of data on

species richness, the density of proposed dam building, and lack of cumulative effects analyses in the Indian Himalaya, our results may underestimate extinction risk and species losses. Additional factors we did not consider include the effects of increased fragmentation of montane vegetation due to other anthropogenic activities, topographic isolation and endemism of biota, and effects of climate change—all of which could result in underestimation of extinction rates (Malcom et al. 2006).

Applications to Conservation Planning

Hydropower is an important energy option for developing countries that need to meet power demands and reduce global carbon emissions. Dams also provide flood control and water for irrigation and drinking. Therefore, it may appear as if the GOI and Indian citizens are willing to trade species losses for the economic and social benefits of dams. But given that ours is the first study to outline potential effects of proposed hydropower development on biological diversity of the Indian Himalaya, it is unknown whether the public, once informed of the consequences, would be willing to choose social goods over ecological benefits. This situation is exacerbated by the fact that the GOI has never carried out studies of the country's future energy requirements that examine alternatives beyond hydropower that may find a reduced need for so many dams (WWF 2007). And, according to a recent study from the Ganga basin, even the assumed social benefits of dams may have little scientific basis (Sadoff et al. 2011). Our results lend support to these claims, but in India, so far, there remains little attention paid to ecological evaluation of large-scale development (Bandyopadhyay & Gyawali 1994; Agrawal 2010).

EIA regulations in India do make assessment of biological diversity "a criterion" for project evaluation. However, lack of scientific studies and poor implementation of EIA processes remain problems, and no projects have been rejected because loss of biological diversity has been cited, except in rare cases involving protected areas and flagship species such as the tiger (*Panthera tigris*) (Singh 2006). In addition, there is no legal requirement in current EIA regulations for analyses of cumulative effects, but given the density of planned dams on all the major rivers in the study area, our results point toward the need to consider this standard in hydropower assessment (Menon & Kohli 2009; Choudhury 2010).

India has the greatest number of people living without electricity (Sargsyan et al. 2010) and the largest civil-society antidam movement in the world. As in many developing nations, this opposition has been based predominantly on social issues, including loss of traditional lands and inequitable resettlement (Choudhury 2010). Up to the present, due to lack of data, there is no precedent for civil groups to consider ecological information in their arguments against dams. However, as more

scientific studies on hydropower effects are completed, the public will likely use them as a tool to critique poorly designed projects. We expect our results to prove useful in establishing an empirical basis for resolving conflicts between conservation and development priorities.

Given the absence of information on effects of dam-building activities on terrestrial ecosystems and their biological diversity, our study assumes more significance because it points toward the need for improved assessment of hydropower development in the Indian Himalaya. At minimum, it would be desirable to locate dams in degraded forest areas and to subject plans for construction of dams in species-rich regions and dense forests to scientific and social investigation before final development decisions are made.

Acknowledgments

Supporting Information

Sources of data related to dams (Appendix S1) and distribution and taxonomic information on various taxonomic groups analyzed for species richness patterns (Appendix S2), basin-wide list of the proposed and under-construction dams and hydroelectric projects and their features (Appendix S3), data on distribution of dams in the Indian Himalayan states, valleys and of different land-cover classes and climatic zones (Appendix S4), estimates of forest area remaining after deforestation and additional forest losses due to dam building in the Himalaya (Appendix S5), data on river basin area and number of dams in major basins of the world (Appendix S6), data on dam features of the proposed and under-construction dams for storage and run-of-the-river (ROR) projects for which feasibility studies and field investigations are either completed or nearing completion (Appendix S7), details of forest land requirement for submergence and for other dam-related activities of 32 dams in the Himalaya for which actual data were available (Appendix S8), and projected extinction of taxa in various taxonomic groups of the Himalaya under various scenarios (Appendix S9) are available online. The authors are responsible for the content and the functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

Literature Cited

Agrawal, D. 2010. Are EIA studies sufficient for projecting hydropower development in the India Himalaya region? Current Science **98:**154–161.

Armitage, P. D., R. J. Gunn, M. T. Furse, J. F. Wright, and D. Moss. 1987. The use of prediction to assess macroinvertebrate response to river regulation. Hydrobiologia **144:**25–32.

Bandyopadhyay, J., and D. Gyawali. 1994. Himalayan water resources: ecological and political aspects of management. Mountain Research and Development **14:**1–24.

Brandt, S. A. 2000. Classification of geomorphological effects downstream of dams. Catena **40:**375–401.

CEA (Central Electric Authority). 2004. Preparation of preliminary feasibility reports (PFRs) under 50,000 MW Hydroelectric Initiative. Central Electricity Authority, New Delhi. Available from www.cea.nic.in/reports/hydro/feasibility_report_50kmw_he.pdf (accessed August 2009).

Choudhury, N. 2010. Sustainable dam development in India. German Development Institute, Bonn.

CISMHE (Centre for Interdisciplinary Studies of Mountain &Hill Environment). 2007. Carrying capacity study of Teesta Basin in Sikkim. Ministry of Environment & Forests, Government of India and NHPC, New Delhi and Faridabad, India.

Congalton, R. S. 2001. Accuracy assessment and validation of remotely sensed and other spatial information. International Journal of Wildland Fire **10:**321–328.

CSE (Centre for Science and Environment). 2011. Cleared for growth. Down to Earth 15 October. Available from http://www.downtoearth.org.in/content/cleared-growth (accessed January 2012).

CWC (Central Water Commission). 1992. Water resources and hydropower potential in India. Government of India, New Delhi.

Dharmadhikary, S. 2008. Mountains of concrete. International Rivers, Berkeley, California.

Drakare, S., J. J., Lennon, and H. Hillebrand. 2006. The imprint of geographical, evolutionary and ecological context on species–area relationships. Ecology Letters **9:**215–227.

Dudgeon, D. 2000. The ecology of tropical Asian rivers and streams in relation to biodiversity conservation. Annual Review of Ecology and Systematics **31:**239–263.

Dynesius, M., and C. Nilsson. 1994. Fragmentation and flow regulation of river systems in the northern third of the world. Science **266:**753–761.

Fahrig, L. 2003. Effect of habitat fragmentation on biodiversity. Annual Review of Ecology, Evolution and Systematics **34:**487–515.

FSI (Forest Survey of India). 2005. The state of forest report 2003. FSI, Ministry of Environment and Forests, Government of India.

Government of India (GOI). 2008. Hydropower policy. Ministry of Power, New Delhi. Available from http://powermin.nic.in/whats_new/pdf/new_hydro_policy.pdf (accessed August 2011).

Grumbine, R., and J. Xu. 2011. Mekong hydropower development. Science **332:**178–179.

Grytnes, J., and O. Vetaas. 2002. Species richness and altitude: a comparison between null models and interpolated plant species richness along the Himalayan altitudinal gradient, Nepal. American Naturalist **159:**294–304.

He, F. L., and S. P. Hubbell. 2011. Species–area relationships always overestimate extinction rates from habitat loss. Nature **473:**368–371.

Irwin, M. T., et al. 2010. Patterns of species change in anthropogenically disturbed forests of Madagascar. Biological Conservation **143:**2351–2362.

Jha, C. S., C. B. S. Dutt, and K. S. Bawa. 2000. Deforestation and land use changes in Western Ghats, India. Current Science **79:**231–238.

Joshi, P. K., S. Singh, S. Agarwal, and P. S. Roy. 2001. Forest cover assessment in western Himalayas, Himachal Pradesh using IRS 1C/1D WiFS data. Current Science **80:**941–947.

Khagram, S. 2004. Dams and development: transnational struggles for water and power. Cornell University Press, New York.

Koh, L. P., T. M. Lee, N. S. Sodhi, and J. Ghazoul. 2010. An overhaul of the species–area approach for predicting biodiversity loss: incorporating matrix and edge effects. Journal of Applied Ecology **47:**1063–1070.

Kowalewski, M., G. E. A. Serrano, K. W. Flessa, and G. A. Goodfriend. 2000. Dead delta's former productivity: two trillion shells at the mouth of the Colorado River. Geology **28:**1059–1062.

Kumar, R., R. D. Singh, and K. D. Sharma. 2005. Water resources of India. Current Science **89:**794–811.

Laurance, W. F., et al. 2002. Ecosystem decay of Amazonian forest fragments: a 22-year investigation. Conservation Biology **16:**605–618.

Lewis, O. T. 2006. Climate change: Species–area curves and the extinction crisis. Philosophical Transactions of the Royal Society B **361:**163–171.

Lomolino, M. V. 2000. Ecology's most general, yet protean pattern: the species-area relationship. Journal of Biogeography **27:**17–26.

Lomolino, M. V. 2001. Elevation gradients of species-density: historical and prospective views. Global Ecology and Biogeography **10:**3–13.

Lovett, R. 1999. As salmon stage disappearing act, dams may too. Science **284:**574–575.

Malcom, J. R., C. Liu, R. P. Neilson, L. Hansen, and L. Hannah. 2006. Global warming and extinctions of endemic species from biodiversity hotspots. Conservation Biology **20:**538–548.

Malmqvist, B., and G. Englund. 1996. Effects of hydropower-induced flow perturbations on mayfly (Ephemeroptera) richness and abundance in north Swedish river rapids. Hydrobiologia **341:**145–158.

May, R. M., and M. P. H. Stumpf. 2000. Species–area relations in tropical forests. Science **290:**2084–2086.

Menon, M., and K. Kohli. 2009. From impact assessment to clearance manufacture. Economic and Political Weekly **44:**20–23.

NACSE (Northwest Alliance for Computation Science & Engineering). 2011. Transboundary freshwater dispute database. Oregon State University, Corvallis. Available from http://ocid.nacse.org/tfdd/index.php (accessed November 24, 2011).

Nandimath, O. V. 2009. Oxford handbook of environmental decision making in India: an EIA model. Oxford, New Delhi.

Nilsson, C., R. Jansson, and U. Zinko. 1997. Long-term responses of river-margin vegetation to water-level regulation. Science **276:**798–800.

Pandit, M. K. 2009. Other factors at work in the melting Himalaya: follow-up to Xu et al. Conservation Biology **23:**1346–1347.

Pandit, M. K., N. S. Sodhi, L. P. Koh, A. Bhaskar, and B. W. Brook. 2007. Unreported yet massive deforestation driving loss of endemic

biodiversity in Indian Himalaya. Biodiversity Conservation **16:**153–163.

Pereira, H. M., and G. C. Daily. 2006. Modeling biodiversity dynamics in countryside landscapes. Ecology **87:**1877–1885.

Poff, N. L., J. D. Olden, D. M. Merritt, and D. M. Pepin. 2007. Homogenization of regional river dynamics by dams and global biodiversity implications. Proceedings of the National Academy of Sciences of the United States of America **104:**5732–5737.

Richter, B., R. Matthews, D. Harrison, and R. Wigington. 2003. Ecologically sustainable water management: managing river flows for ecological integrity. Ecological Applications **13:**206–224.

Sadoff, C., et al. 2011. The Ganges strategic basin assessment. World Bank, World Water Week, Stockholm, Sweden. Available from http://www.worldwaterweek.org/documents/WWW_PDF/2011/Sunday/K23/Promoting-Cooperation-in-the-Ganges-Basin-through-Dialog/The-Ganges-Strategic-Basin-Assessment.pdf (accessed August 2011).

Sagar, R., A. Raghubanshi, and J. Singh. 2003. Tree species composition, dispersion and diversity along a disturbance gradient in a dry tropical forest region of India. Forest Ecology and Management **186:**61–71.

Sargsyan, G. et al. 2010. Unleashing the potential of renewable energy in India. World Bank, Washington, D.C.

Singh, J. S. 2006. Sustainable development of the Indian Himalayan region: Linking ecological and economic concerns. Current Science **90:**784–788.

Terborgh, J. 1974. Preservation of natural diversity: the problem of extinction prone species. BioScience **24:**715–722.

Terborgh, J., et al. 2001. Ecological meltdown in predator-free forest fragments. Science **294:**1923–1926.

Trzcinski, M., L. Fahrig, and G. Merriam. 1999. Independent effects of forest cover and fragmentation on the distribution of forest breeding birds. Ecological Applications **9:**586–593.

Ulrich, W. 2005. Predicting species numbers using species-area and endemics-area relations. Biodiversity and Conservation **14:**3351–3362.

Vellend, M., K. Verheyen, H. Jacquemyn, A. Kolb, H. Van Calster, G. Peterken, and M. Hermy. 2006. Extinction debt of forest plants persists for more than a century following habitat fragmentation. Ecology **87:**542–548.

Ward, J. 1976. Effects of flow patterns below large dams on stream benthos: a review. Pages 235–253 in J. Orsborn and C. Allman, editors. Instream flow needs symposium. Volume 2. American Fisheries Society, Bethesda, Maryland.

Wieringa, M., and A. Morton. 1996. Hydropower adaptive management and Biodiversity. Environmental Management **20:**831–840.

WWF (World Wildlife Fund). 2007. Climate solutions. WWFs vision for 2050. WWF International, Gland, Switzerland.