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Busch, J., Dave, R., Hannah, L., Cameron, A., Rasolohery, A., Roehrdanz, P., & Schatz, G. (2012). Climate change and the cost of conserving species in Madagascar. *Conservation Biology*, 26(3), 408–419. Advance online publication. <https://doi.org/10.1111/j.1523-1739.2012.01838.x>

**Published in:**  
Conservation Biology

**Document Version:**  
Peer reviewed version

**Queen's University Belfast - Research Portal:**  
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# Climate Change and the Cost of Conserving Species in Madagascar

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**Abstract:** *We examined the cost of conserving species as climate changes. We used a Maxent species distribution model to predict the ranges from 2000 to 2080 of 74 plant species endemic to the forests of Madagascar under 3 climate scenarios. We set a conservation target of achieving 10,000 ha of forest cover for each species and calculated the cost of achieving this target under each scenario. We interviewed managers of projects to restore native forests and conducted a literature review to obtain the net present cost per hectare of management actions to maintain or establish forest cover. For each species, we added hectares of land from lowest to highest cost per additional year of forest cover until the conservation target was achieved throughout the time period. Climate change was predicted to reduce the size of species' ranges, the overlap between species' ranges and existing or planned protected areas, and the overlap between species' ranges and existing forest. As a result, climate change increased the cost of achieving the conservation target by necessitating successively more costly management actions: additional management within existing protected areas (US\$0–60/ha); avoidance of forest degradation (i.e., loss of biomass) in community-managed areas (\$160–576/ha); avoidance of deforestation in unprotected areas (\$252–1069/ha); and establishment of forest on nonforested land within protected areas (\$802–2710/ha), in community-managed areas (\$962–3226/ha), and in unprotected areas (\$1054–3719/ha). Our results suggest that although forest restoration may be required for the conservation of some species as climate changes, it is more cost-effective to maintain existing forest wherever possible.*

**Keywords:** adaptation, biodiversity conservation, deforestation, forest restoration

Cambio Climático y el Costo de la Conservación de Especies en Madagascar

**Resumen:** *Para examinar el costo de la conservación de especies a medida que cambia el clima, utilizamos un modelo Maxent de distribución de especies para predecir los rangos de distribución 2000–2080 de 74 especies de plantas endémicas a los bosques de Madagascar bajo 3 escenarios. Definimos como meta de conservación alcanzar 10,000 ha de bosque para cada especie y calculamos el costo de alcanzar esta meta en cada escenario. Entrevistamos gestores de proyectos de restauración de especies nativas en los bosques y revisamos la literatura para obtener el costo neto actual por hectárea de las acciones de manejo para mantener o establecer la cobertura forestal. Para cada especie, agregamos hectáreas de terreno desde el costo más bajo al más alto por año adicional de cobertura forestal hasta que se alcanzaba el objetivo de conservación en el período de tiempo. Se predijo que el cambio climático reduciría la extensión de la distribución de especies, del traslape de rangos de especies y de las áreas protegidas existentes o planificadas, y*

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Paper submitted November 05, 2010; revised manuscript accepted October 09, 2011.

*el traslape entre los rangos de especies y el bosque existente. Como resultado, el cambio climático incrementó el costo para alcanzar la meta de conservación al requerir de acciones sucesivas de manejo cada vez más costosas: manejo adicional dentro de áreas protegidas existentes (US\$0–60/ba); evitar la deforestación en áreas no protegidas (\$252–1069/ba); establecimiento de bosque en terrenos no forestales dentro de áreas protegidas (\$802–2710/ba), en áreas manejadas por la comunidad (\$962–3226/ba), y en áreas no protegidas (\$1054–3719/ba). Nuestros resultados sugieren que, aunque se puede requerir la restauración de bosques para la conservación de algunas especies a medida que cambia el clima, es más rentable mantener el bosque existente donde sea posible.*

**Palabras Clave:** adaptación, conservación de la biodiversidad, deforestación, restauración de bosques

## Introduction

New temperature and precipitation patterns associated with climate change are expected to shift species' ranges (Peters & Darling 1985; Parmesan 1996). Species with current ranges that overlap protected areas may move to areas where their habitat is unprotected (Araujo et al. 2004). Species' survival in future climates (Thomas et al. 2004; Sinervo et al. 2010) and strategies for conserving species as climate changes (Hannah et al. 2007) have been explored previously. Researchers have begun to examine the cost of conservation in a changing climate (Shaw et al. 2012; Wise et al. 2012).

To protect the many endemic species of Madagascar (Myers et al. 2000; Goodman & Benstead 2005), the government committed at the World Parks Congress in 2003 to tripling the area covered by the country's networks of terrestrial and marine protected areas by 2012. This expansion is underway. Bilateral and multilateral agencies and conservation groups have provided over US\$150 million to Madagascar for conservation since 1997 (World Bank 2008a), including funds for the expansion of protected areas.

Although the planned protected-area network encompasses current habitat for endemic species (Kremen et al. 2008), the long-term success of the network depends on the extent to which it will continue to provide habitat given changes in climate and land use. Movements of montane endemic amphibians and reptiles to higher elevations have already been observed in Madagascar and are consistent with predictions of species' responses to increasing temperatures (Raxworthy et al. 2008). Some species may be unable to move as the distribution of their habitat changes, particularly where anthropogenic land use has created barriers between areas of habitat.

The resilience of Madagascar's terrestrial species to climate change depends on the maintenance and restoration of the forest that serves as their habitat. Recommended actions to reduce the effect of climate change on Madagascar's terrestrial species include facilitating needed changes in species' ranges by reducing deforestation in remaining natural forests, restoring connectivity between isolated forest fragments, and restoring natural forests along rivers. It is also recommended that forest management provide for human adaptation to climate change (Hannah et al. 2008).

Conservation in Madagascar takes place in the context of widespread poverty, which is both a cause and a consequence of forest loss. Eighty-five percent of Madagascar's population survives on <US\$2/d (World Bank 2008b), and approximately 80% of Madagascar's population lives in rural areas and relies on subsistence agriculture (Kistler & Spack 2003). Shifting slash-and-burn cultivation of rice, known as *tavy*, is a main driver of deforestation throughout much of Madagascar (Erdmann 2003). Furthermore, the 17 million Malagasy consume 22 million m<sup>3</sup> of wood annually for cooking and construction (Rabenandrasana 2007). Due to these and other human activities, forest cover in Madagascar decreased by almost 40% from the 1950s to 2000 (Harper et al. 2007) and by 4.3% from 2000 to 2010 (FAO 2010). Today 16% of Madagascar is covered by fragments of natural forest (MEFT et al. 2009), reduced from 28% in the 1950s (Harper et al. 2007). Loss of forest has led to soil erosion and sedimentation of streams and rivers. Protected areas encompass forests at the headwaters of rivers that provide 8.4 million m<sup>3</sup> of drinking water and irrigation water for 431,000 ha of cropland (Carret & Loyer 2003). Loss of habitat for charismatic fauna such as lemurs and chameleons affects Madagascar's tourism industry, which provides a substantial portion of the country's employment and income (a reported 5.1% of jobs and 6.3% of gross domestic product) (WTTC 2008).

Given this widespread dependence on natural resources, conservation plans in Madagascar generally include a focus on poverty alleviation. Most protected areas established since 2003 are co-managed by the national government and local communities and correspond to the International Union for Conservation of Nature (IUCN) protected-area categories V and VI (protected landscape and protected area with sustainable use of natural resources, respectively). Conversion of forests for agricultural use is prohibited in these areas, but extraction of timber and non-timber products for local use is permitted. Many new conservation projects focus on forest restoration, which can provide income and natural resources to communities, or on commodity substitution, which aims to provide communities with a supply of wood products (e.g., firewood and charcoal) from plantation forests rather than native forests.

We estimated the costs associated with conserving plant species endemic to the forests of Madagascar as

climate changes. We focused on the maintenance and establishment of forest that serves as habitat for those species. Given the potential for conservation projects to alleviate poverty, we focused on restoration of native forests, commodity substitution, and management of the planned protected-area network. A common and realistic conservation target is to secure the minimum area of habitat necessary to ensure a species' persistence. We applied this target to 74 plant species endemic to Madagascar. We calculated the cost of achieving this target for each species for 4 time intervals (2000, 2000–2020, 2000–2050, and 2000–2080) and for 3 scenarios of greenhouse-gas emissions (no climate change, low greenhouse-gas emission increases, and business-as-usual increases in greenhouse-gas emissions).

## Methods

We obtained spatial projections of climate in Madagascar for 2000 from WorldClim (2011) (30 arc-second resolution [approximately  $900 \times 900$  m]). We obtained climate projections for 2020, 2050, and 2080 for the A2a scenario of the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), in which annual greenhouse-gas emissions continue to accelerate along a “business as usual” pathway, and the B2a scenario, in which annual greenhouse-gas emissions are lowered relative to the business-as-usual pathway (IPCC 2007), from the Hadley Centre's HadCM3 Coupled Atmospheric–Oceanic General Circulation Model (Johns et al. 2003). The HadCM3 model of the business-as-usual emissions scenario projects that decadal mean surface temperatures in Madagascar will increase by  $3.1^\circ\text{C}$  above the preindustrial level by 2080 and average precipitation will decrease by 10% overall with regional variation. The HADCM3 model of the low-emissions scenario projects that decadal mean surface temperatures in Madagascar will increase by  $2.2^\circ\text{C}$  by 2080 and average precipitation across Madagascar will decrease by 4% overall with regional variation. In a counterfactual scenario (no climate change), we held decadal mean temperature and precipitation from 1950 to 2000 constant through 2080. We compared these results with results obtained under 2 alternative general circulation models produced by the Commonwealth Scientific and Industrial Research Organisation, Australia (Gordon et al. 2002), and the Canadian Center for Climate Modelling and Analysis (Flato et al. 2000).

We used Maxent (Phillips et al. 2006; Phillips & Dudík 2008) to model the distributions of 74 species of plants endemic to Madagascar in each time period given each climate scenario. All species were woody shrubs or trees associated with primary forest or woody ecosystems; none regenerate in secondary vegetation. All species occurred in at least 7 locations (G.S. et al., unpublished). We se-

lected species to represent all primary woody vegetation types (humid forest, subhumid forest, dry forest, and sub-arid forest, bushland, and thicket), with the exception of those in the montane bioclimatic zone. In addition, we selected species to maximize representation of endemism at higher taxonomic levels. Sixty of the 74 species are members of endemic genera and 42 are members of endemic families.

We used 9 climate variables to project species ranges (Kremen et al. 2008). We also included as a continuous variable percent forest cover in 2000 (30 arc-second grid resolution derived from forest cover change maps at 28-m resolution) (Harper et al. 2007). We assumed percent forest cover remained constant in future periods. Projections of future species ranges were constrained by current values of climate variables across Madagascar, so we did not make projections for locations where future values of climate variables exceeded current values. Such locations represented <2% of land area by 2080 in the low-emissions scenario and <4% of land area by 2080 in the business-as-usual emissions scenario.

We divided the land surface of Madagascar into 736,280 grid cells with a resolution of 30 arc second. For each cell, we calculated the area of land in each of 6 land management classes on the basis of 2 classes of forest cover (forest and nonforest) (Harper et al. 2007) and 3 classes of protected status (protected areas managed for biological diversity; community-managed areas managed jointly by government and communities for extraction of wood by the community; and unprotected land outside protected areas). We classified the protection status of existing and proposed protected areas (Government of Madagascar 2008) on the basis of these areas' IUCN protected-area categories. We classified all proposed protected areas as community managed.

For each of the 6 classes of land management, we estimated the per-hectare cost of maintaining or establishing a stable area of native forest cover on the basis of interviews and gray literature (described later). We considered native forest cover stable if it occurred within a protected area or within a community-managed area in which deforestation (the conversion of forest to nonforest) and forest degradation (loss of biomass within forest that is not converted) is avoided through management actions. We assumed that any native forest outside of such protected areas or community-managed areas would be cleared by 2080 and that nonforested areas would not become forest in the absence of human intervention. We assumed that native forest established on nonforested land was equivalent to mature native forest over the temporal extent of analyses. The spatial configuration of forest did not affect its designation as stable. To account for uncertainties in cost estimation, we estimated both a high and low per-hectare cost for each land management class. We converted all costs to net present 2008 U.S. dollars to compare the costs of management actions occurring

**Table 1. Net present cost per hectare of maintaining or establishing native forest cover with current classes of land management.**

<i>Land management class</i>	<i>Additional management within protected areas (\$/ha)<sup>a</sup></i>	<i>Wood-product substitution (\$/ha)<sup>b</sup></i>	<i>Establishing community management (\$/ha)<sup>c</sup></i>	<i>Wood or agricultural product substitution (\$/ha)<sup>d</sup></i>	<i>Native forest restoration (\$/ha)<sup>e</sup></i>	<i>Total (\$/ha)</i>
Forest in protected area	0–60	–	–	–	–	0–60
Forest in community-managed area						
land acquisition		0–311				
plantation		160–265				
total	–	160–576				160–576
Forest outside managed area	–	–	92–189	160–880	–	252–1069
Nonforest in protected area <sup>f</sup>						
start-up					105–229	
recurring					697–2421	
total	0–60	–	–	–	802–2650	802–2710
Nonforest in community-managed area <sup>f</sup>						
land acquisition		0–311				
plantation		160–265				
start-up					105–229	
Recurring					697–2421	
total	–	160–576	–	–	802–2650	962–3226
Nonforest outside managed area						
start-up					105–229	
recurring					697–2421	
total	–	–	92–189	160–880	802–2650	1,054–3719

<sup>a</sup> Carret and Loyer (2003).

<sup>b</sup> Lopez et al (2007), Rabenandrasana et al. (2007), and authors' calculations (see Methods).

<sup>c</sup> Meyers et al (2005) and authors' calculations (see Methods).

<sup>d</sup> Lopez et al (2007), B. Minten (unpublished), and authors' calculations (see Methods).

<sup>e</sup> Primary survey research conducted for this paper.

<sup>f</sup> Start-up costs: costs of obtaining land rights, community consultation, and scientific research; recurring costs: costs of labor, trees, materials, maintenance, transportation, training, and administration.

at different times (Supporting Information). Depending on an area's current land management class, the cost of maintaining or establishing native forest cover included restoration of native forest, avoided forest degradation, avoided deforestation, or additional management within protected areas (Table 1).

On nonforested land, we estimated the per-hectare cost of forest restoration by interviewing the managers of 13 projects to restore native forests. We identified restoration projects through discussions with more than 30 experts in the government, bilateral aid agencies, and non-governmental organizations. We conducted in-person interviews with project managers in July and August 2008. We asked project managers to state total and component (e.g., obtaining land rights, community consultation, and scientific research) costs of initiating the project and total and component (e.g., labor, trees and materials, maintenance, transportation, training, and administration) recurring costs. When both budgeted and incurred costs per hectare were available for the same project, we used

the incurred costs. The survey instrument is in Supporting Information.

Per-hectare net present costs of restoration of native forest ranged from \$291/ha to \$20,000/ha (median cost \$1,521/ha). The wide variation across projects in the per-hectare cost of restoration can be explained by differences in forest type, soil type, distance between restoration site and mature forest, density of trees planted per hectare, use of local labor, and years since project establishment. To account for the range of costs while providing estimates that are insensitive to outlying values, we selected the 25th percentile costs (\$802/ha) and 75th percentile costs (\$2650/ha) for the low-cost and high-cost scenarios. Start-up costs and recurring costs were \$105–229/ha and \$697–2421/ha, respectively.

In community-managed areas, we assumed degradation of native forests could be avoided by substituting wood products that local people obtain from native forests (construction materials, firewood, and charcoal) with the same products from plantation forests. We assumed the



values of wood products from native forests and plantation forests were equal. We calculated the per-hectare cost of avoiding degradation in native forests through wood-product substitution as

$$C_{AD} = \frac{X_{NF}}{X_P(C_P + C_{LA})}, \quad (1)$$

where  $C_{AD}$  is per-hectare cost of avoiding degradation of native forest,  $C_P$  is the net present cost per hectare of planting and replanting a plantation forest (e.g., at 5-year intervals [Lopez et al. 2007]),  $C_{LA}$  is the cost of acquiring land for plantation forestry,  $X_{NF}$  is the annual quantity of usable wood per hectare of native forest, and  $X_P$  is the annual quantity of usable wood per hectare of plantation forest. In the low-cost scenario, we derived plantation costs and wood quantity through analyses of a *Eucalyptus camaldulensis* wood-substitution program in the Antsiranana (Diego Suarez) dry-forest region (Lopez et al. 2007). We used  $C_P = \$1097/\text{ha}$ ,  $C_{LA} = \$0/\text{ha}$ , and  $X_{NF}/X_P = 0.146$  to calculate the low per-hectare cost of avoiding degradation through wood-product substitution:  $\$160/\text{ha}$ .

In the high-cost scenario, we derived plantation costs from analyses of a wood-substitution program that used *Acacia mangium*, *Casuarina equisetifolia*, *E. camaldulensis*, and *Eucalyptus robusta* in the Toalagnaro (Ft. Dauphin) wet-forest region (Rabenandrasana 2007). We used  $C_P = \$750/\text{ha}$ ,  $C_{LA} = \$880/\text{ha}$ , and  $X_{NF}/X_P = 0.354$  to calculate the high per-hectare cost of avoiding degradation through wood-product substitution:  $\$265/\text{ha}$ . In the low-cost scenario, we assumed the cost of land acquisition would be zero due to a sufficient quantity of nonforest land available for plantation forestry within market distance, for example from within the community-managed area itself. In the high-cost scenario we assumed such land would have to be acquired at a cost of agricultural product substitution (explained later).

In unprotected areas, we assumed deforestation could be avoided through the provision of agricultural products to local communities as a substitute for either gathering of wood products or production of rice. The low-cost estimate of avoided deforestation included only substitution for wood products, as described earlier. The high-cost estimate included only substitution for rice production. We based the cost of rice substitution on the results of a study in the Maraonsetra region that showed a net present value of farmers' median annual stated willingness to accept payment in rice in exchange for ceasing tavy practices of  $\$880/\text{ha}$  (B. Minten, unpublished). In the absence of comparable studies elsewhere in Madagascar, we assumed this figure was representative of the entire country.

The per-hectare cost of maintaining stable native forest in unprotected areas also included the cost of establishing community management. We derived cost estimates for the establishment of community management in Mada-

gascar from Meyers et al. (2005), who found low and high costs for management of a medium-sized (2,000–20,000 ha) conservation site to be  $\$7.38\text{--}15.15/\text{ha}$  annually, corresponding to net present costs of  $\$92\text{--}189/\text{ha}$ .

The per-hectare cost of maintaining a stable area of native forest within protected areas was the currently unmet, relatively minor, cost of additional management activities such as monitoring and enforcement. In the low-cost scenario, we assumed these costs were zero (all costs currently met). In the high-cost scenario, we assumed an annual cost of  $\$5/\text{ha}$  (net present cost of  $\$60/\text{ha}$ ), which we derived from a study of costs of protected-area management (Carret & Loyer 2003).

### Per-Species Cost of Achieving Stable Area of Native Forest

For each species, we calculated the network of sites across which more than 10,000 ha (100 km<sup>2</sup>) of stable native forest could be maintained or established within the species' range—during each time step of 4 successively longer time periods 2000, 2000–2020; 2000–2050; 2000–2080). Plant species with <10,000 ha of habitat are classified as “very restricted” by IUCN (2011). We used the 10,000-ha target for all plant species and assumed all forest types were equivalent. With millions of sites, it is analytically intractable to solve for the network of sites that provides the minimum area of stable cover of native forest at the lowest cost. Thus, we used a simple (greedy) algorithm that added sites to the network from lowest to highest cost per additional time steps of forest gained until the minimum area of native forest was achieved in all time steps. This algorithm did not explicitly require that patches of forest included in the network be contiguous or have a minimum size. That is, sites were rank-ordered for addition to the network on the basis the following cost-benefit ratio

$$\frac{c_i}{\sum_{t=2000}^{\bar{t}} A_i x_{ist} p_{st}}, \quad (2)$$

where  $c_i$  is the cost of maintaining or establishing native forest cover at site  $i$  ( $\$0\text{--}60$  for forest in protected areas;  $\$160\text{--}576$  for forest in community-managed areas;  $\$252\text{--}1069$  for forest in unprotected areas;  $\$802\text{--}2710$  for nonforest in protected areas;  $\$962\text{--}3226$  for nonforest in community-managed areas; and  $\$1074\text{--}3719$  for nonforest in unprotected areas);  $A_i$  is the area of site  $i$ ;  $x_{ist}$  is a binary variable equal to one if site  $i$  is within the range of species  $s$  in time step  $t$  and equal to zero otherwise;  $p_{st}$  is a binary variable that is equal to one if species  $s$  has <10,000 ha of stable forest in time step  $t$  and equal to zero otherwise; and  $\bar{t}$  is the final time step in the analyzed time period  $T$  (where  $\bar{t} \in \{2000, 2020, 2050, 2080\}$  and  $T \in \{2000, 2000\text{--}2020, 2000\text{--}2050, 2000\text{--}2080\}$ ). We

**Table 2.** Number of 74 endemic species of plants in Madagascar for which ranges are projected to decrease further into the future or as greenhouse gas emissions increase.

<i>Climate-change scenario and period*</i>	<i>Total range</i>	<i>Range within protected areas or community-managed areas</i>	<i>Range within forested areas</i>
Further into the future, low-emissions scenario			
2020 versus 2000	40	39	38
2050 versus 2020	40	41	42
2080 versus 2050	65	61	58
Further into the future, business-as-usual scenario			
2020 versus 2000	42	41	40
2050 versus 2020	44	44	47
2080 versus 2050	61	60	59
Increased emissions, 2020			
low-emissions versus no climate change	40	39	38
business-as-usual versus low-emissions	36	35	40
business-as-usual versus no climate change	42	41	40
Increased emissions, 2050			
low-emissions versus no climate change	42	35	35
business-as-usual versus low-emissions	48	50	52
business-as-usual versus no climate change	44	43	42
Increased emissions, 2080			
low-emissions versus no climate change	48	48	45
business-as-usual versus low-emissions	58	55	57
business-as-usual versus no climate change	56	56	55

\*Low-emissions represents the IPCC B2a climate-change scenario (IPCC 2007). Business-as-usual represents the IPCC A2a climate-change scenario (IPCC 2007).

recalculated the rank order in Eq. 2 each time the minimum area of forest was achieved for the species in one of the time steps of the analyzed period. Thus, the total cost of achieving minimum area of forest for species  $s$  in all time steps  $t$  in analyzed time  $T$  was

$$C_{sT} = \sum_{i=1}^{\bar{i}} c_i, \quad (3)$$

where  $\bar{i}$  represents the final site added to the network to achieve minimum area of forest for the species in all time steps.

## Results

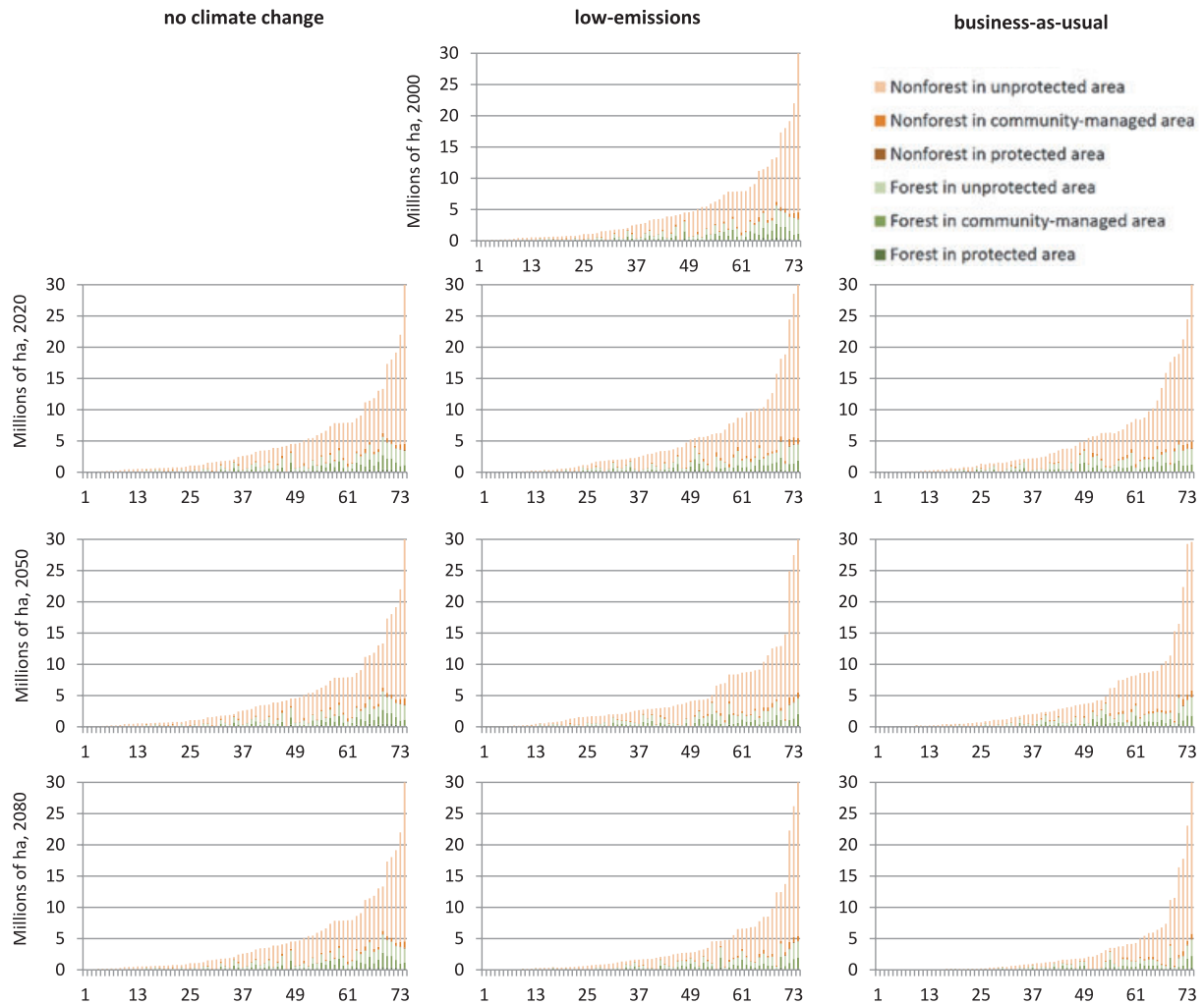
The per-hectare cost of achieving stable forest cover on forested land in Madagascar was \$0–60/ha in protected forests, \$160–576/ha in community-managed forests, and \$252–1069 in unprotected forests. By comparison, the per-hectare cost of achieving stable forest cover on non-

forested land was \$802–2710/ha within protected areas, \$962–3226/ha within community-managed areas, and \$1054–3719/ha within unprotected areas.

As climate changed over time or as the greenhouse-gas-emissions scenario driving climate change increased, the ranges of 74 endemic plant species in Madagascar generally decreased. The areas of species' ranges that overlapped with forest, with protected areas, or with community-managed areas decreased as well (Table 2, Fig. 1, & Supporting Information). Using the alternative general circulation models, we obtained consistent results.

As the area of species' ranges in forest or protected areas decreased, the per-species cost of achieving minimum stable forest cover increased (Figs. 2 & 3). Because the area of protected forest decreased, more forest had to be maintained on unprotected land, or established on nonforested land, to achieve the 10,000-ha target. Such actions were successively more expensive.

As the greenhouse-gas-emissions scenario driving climate change increased from no climate change to



**Figure 1.** Species' projected range sizes under 3 climate-change scenarios. Species are rank ordered from smallest to largest area across x-axis. Color indicates the area of range size within each land management class.

low-emissions to business-as-usual emission increases, the cost of achieving the conservation target increased. The median per-species cost of achieving the minimum area of stable forest cover increased from \$0–603,400 to \$0–604,100 to \$0–604,500 for 2000–2020; from \$0–603,400 to \$0–604,500 to \$847,000–3,782,000 for 2000–2050; and \$0–603,400 to \$935,900–4,094,600 to \$1,242,000–5,192,300 for 2000–2080 (Figs. 2 & 3). The range of costs reflected low and high cost assumptions. As the length of time over which minimum area of stable forest cover must be maintained increased (from 2000 to 2000–2020 to 2000–2050 to 2000–2080), the cost of achieving the conservation target increased. The median per-species cost of securing minimum stable forest cover increased from \$0–603,400 to \$0–604,100 to \$0–604,500 to \$935,900–4,094,600 in the low-emissions scenario and from \$0–603,400 to \$0–604,500 to \$847,000–\$3,782,000 to \$1,242,000–5,192,300 in the business-as-usual emission increases scenario.

## Discussion

We found that maintaining existing forest, for example by avoiding forest degradation and deforestation through the creation of substitute sources of wood products and agricultural commodities, was considerably cheaper and quicker to apply than restoring forest once it had been cleared.

As climate changed over time, or as the greenhouse-gas-emissions scenario driving climate change increased, the ranges of the 74 forest-associated plant species shifted, the area of range overlap with protected areas decreased, and the area of range overlap with existing forest decreased. Thus, the cost of management actions necessary to maintain a minimum area of stable forest cover increased.

Climate change imposes 5 additional costs on the conservation of species. First is the cost of planning to design a network of sites that will maintain a stable area of habitat



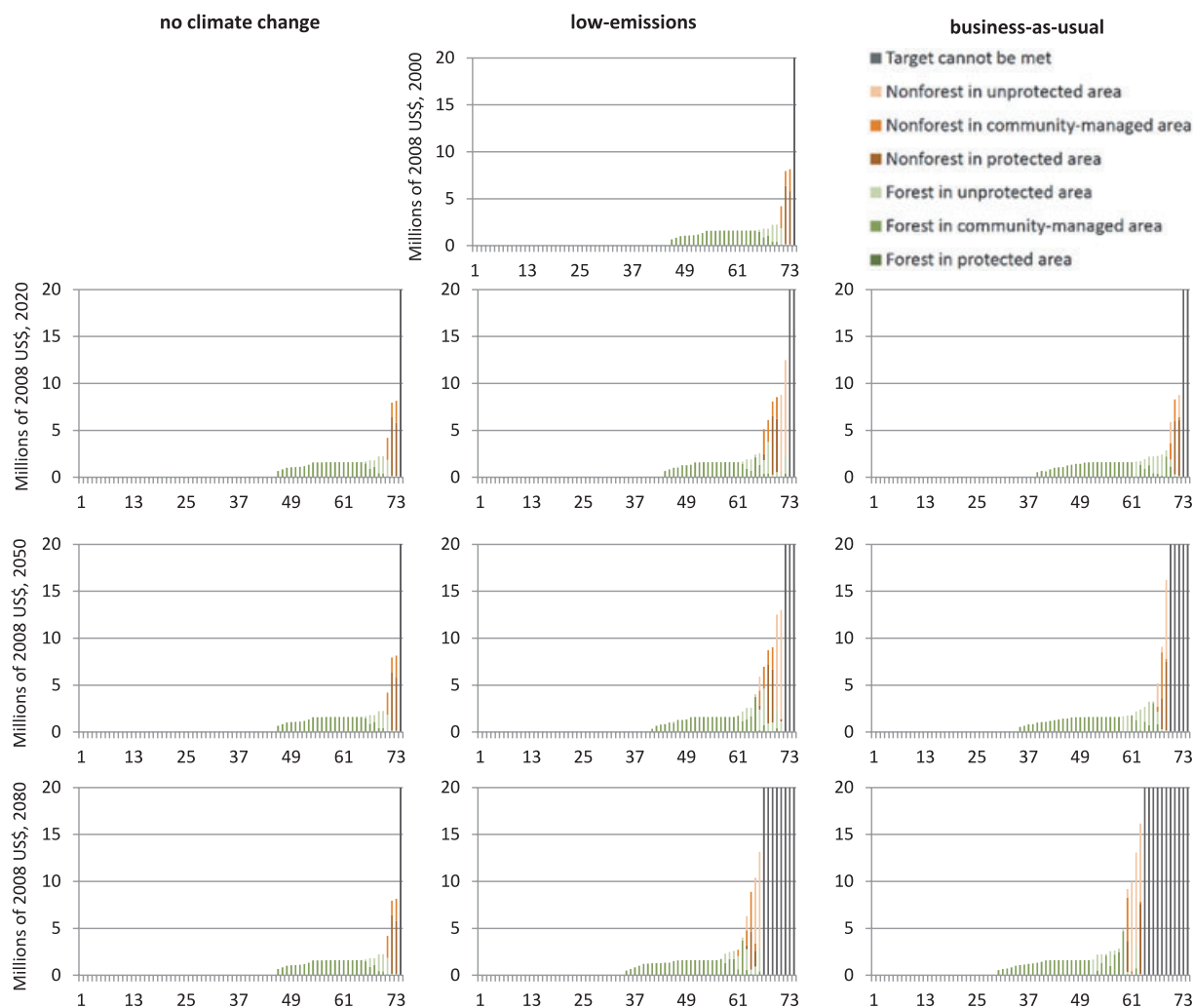


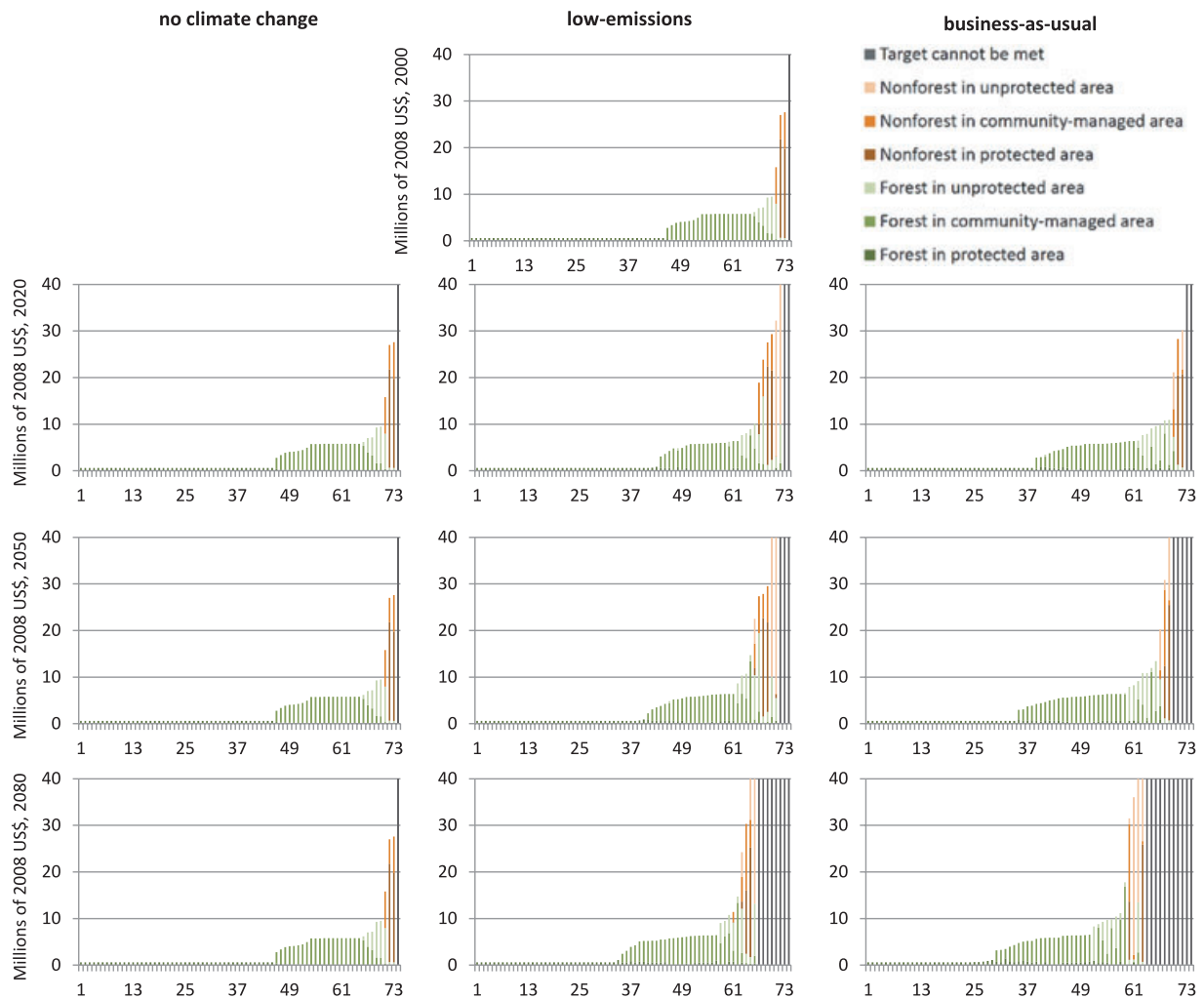
Figure 2. Cost of achieving a minimum area of native forest with low cost assumptions under 3 climate-change scenarios. Species are rank ordered from smallest to largest cost across x-axis. Color indicates the portion of the cost spent for each class of land management.

for species given future range shifts as climate changes. Planning may change the locations selected for management actions without increasing the cost of actions. For the Za baobab (*Adansonia za*) (Fig. 4a), a widespread species classified by IUCN (2011) as near threatened, the cost of achieving a minimum area of stable forest cover with forests in protected areas did not change.

Second is the cost of extending management actions across a larger area. Even for species for which relatively large portions of their ranges were protected in every time step, ranges shifted and range overlap with protected areas decreased. This means management across a larger total area would be necessary to achieve 10,000 ha of stable forest cover from 2000 through 2080. For the octopus tree (*Alluaudiopsis marnieriana*) (Fig. 4b), a spiny succulent of the semiarid to sub-arid spiny forest of southern Madagascar whose trade is regulated by the Convention on International Trade

in Endangered Species of Wild Fauna and Flora (CITES) (IUCN 2011), costs increased given climate change because larger areas of protected forest are required to achieve a minimum area of stable forest cover through time.

Third is the cost of maintaining forest outside currently protected or community-managed areas. Because climate change decreased the size of species' ranges within protected or community-managed forest, maintaining forest in unprotected areas became increasingly necessary to achieve the target of 10,000 ha of stable forest cover. Maintaining forest was more expensive in unprotected areas than in protected or community-managed areas. For the hazompasina (*Rhodolaena acutifolia*) (Fig. 4c), a flowering species with a restricted range that occurs at relatively low elevation in evergreen forest (IUCN 2011), costs increased given climate change as forest outside protected areas or community-managed areas became



**Figure 3.** Cost of achieving a minimum area of native forest with high cost assumptions under 3 climate-change scenarios. Species are rank-ordered from smallest to largest cost across x-axis. Color indicates the portion of the cost spent for each class of land management.

necessary to achieve a minimum area of stable forest cover.

Fourth is the cost of establishing forest on nonforested land. Because climate change decreased the size of species' ranges within forest, establishing native forest through reforestation or afforestation became increasingly necessary to achieve the 10,000-ha target. Establishing new forest was more expensive than maintaining existing forest. For the Scott-Elliot capuron (*Rhopalocarpus coriaceus*), a tree associated with littoral forest (IUCN 2011), costs increased under the low-emissions scenario because achieving a minimum area of stable forest cover required establishment of new forest in addition to the maintenance of current forest (Fig. 4d).

Fifth is the cost of intensive species management or ex situ conservation. When climate change decreased the sizes of species' ranges below 10,000 ha, the target for area of stable forest cover was not met through forest maintenance or restoration alone at any cost. We

did not calculate the costs of intensive species management or ex situ conservation, but these costs are likely to be greater than forest maintenance or restoration. For the Scott-Elliot capuron, the target could not be met under the business-as-usual increase in emissions scenario (Fig. 4d). For the endra-endra (*Humbertia madagascariensis*), a tree in low-elevation humid forests (IUCN 2011), the target could not be met under either the low-emissions or the business-as-usual increase in emissions climate-change scenarios (Fig. 4e).

Our results showed that lower greenhouse-gas emissions reduce the cost of species conservation. Some level of climate change is inevitable. However, concerted global efforts to reduce emissions of greenhouse gases could shift climate change from its current trajectory, which is most similar to the business-as-usual emissions increases scenario, to a trajectory more similar to the low-emissions scenario. Our results indicate that such a shift would lower the median cost of achieving a minimum

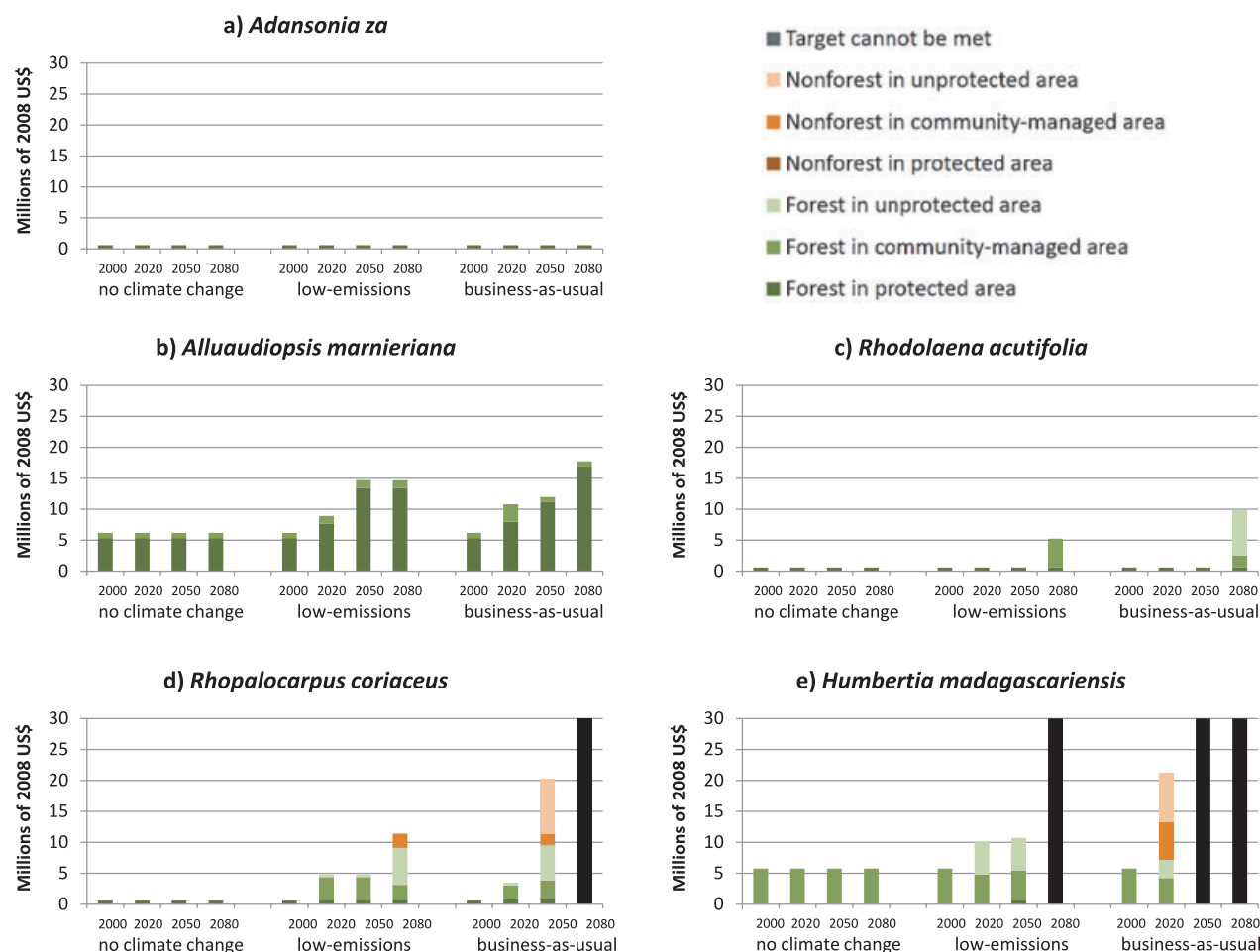


Figure 4. Cost of achieving a minimum area of native forest with high cost assumptions under 3 climate-change scenarios for 5 species (a–e). Color indicates the portion of cost spent within each class of land management.

area of stable forest cover through 2080 for an endemic plant species in Madagascar from \$1,242,000–5,192,300 to \$935,900–4,094,600 and would decrease the number of species for which intensive management or ex situ conservation may be required from 11 to 8.

A number of caveats apply to our estimates of the cost of restoration of native forest. The number of restoration projects from which we derived cost estimates was small ( $n = 13$ ). Costs were self-reported. Projects were frequently located at the most suitable or cheapest sites for restoration, so may not be representative of projects at other sites. Many projects were too new for their effectiveness at restoring forest to have been assessed, although in most cases short-term plant survival was high. It will be decades before replanted seedlings will be biologically equivalent to mature forest. The effect that forest restoration ultimately may have on species' ability to move as climate changes is unknown. We based estimates of the effectiveness and cost-effectiveness of avoiding degradation and deforestation through product

substitution on even fewer projects and these estimates are even more uncertain.

Future work can build on our analyses in at least 3 ways. First, estimates of the costs of management actions would benefit from larger, long-term, forest-restoration, avoided-deforestation and avoided-degradation projects from which to gather primary cost data. These projects need not be limited to wood and agricultural product substitution. Second, a conservation-planning optimization exercise for Madagascar species under climate change could help identify and prioritize units of land that would provide habitat for multiple species simultaneously. Our selected species were adequate to illustrate rising costs of single-species conservation as climate changes; examination of more species is needed to identify priority sites for conservation or to estimate aggregate costs given the returns to scale that would accrue from a multiple-species approach. Third, the cost of conservation as climate changes could be studied for other species, climate-change scenarios, and geographic regions.

We believe that our findings apply to other tropical regions with little remaining forest cover and high rates of deforestation (da Fonseca et al. 2007), including the Philippines, Western Ghats, Atlantic Forest of Brazil, Mesoamerica, and West Africa (Myers et al. 2000). In these regions, as in Madagascar, conservation of some species, as climate changes, is likely to require connection of forest patches. The relative difference between the cost of avoided deforestation and avoided forest degradation and the cost of restoration of native forest in these regions may be similar. In these regions, as in Madagascar, national economic and poverty alleviation priorities likely preclude near-term domestic funding for forest conservation and restoration at the magnitude required for conservation of forests as climate changes.

Forest maintenance and restoration may provide both monetary and nonmonetary benefits to local people. A portion of the cost of avoiding native forest deforestation and degradation might be recovered through international carbon payments (e.g., Reduced Emissions from Deforestation and Forest Degradation [REDD]). The cost of restoring native forests might be partially recovered through afforestation and reforestation mechanisms of a global climate agreement (e.g., the Clean Development Mechanism of the Kyoto Protocol or REDD+). Another portion of the cost could be justified by the provision of clean water for drinking and farming (Carret & Loyer 2003). Native forests also provide sustainable sources of medicine, food, and construction materials and potentially revenue from nature-based tourism. However, even though forests in Madagascar and similar regions provide potential monetary and nonmonetary benefits, forest protection and restoration appears likely to require continued external support.

International finance for some types of forest maintenance and restoration might eventually be provided through adaptation provisions of the United Nations Framework Convention on Climate Change (UNFCCC). In the UNFCCC Cancun Decisions, developed countries pledged \$30 billion from 2010 to 2012 for climate-change adaptation and mitigation and stated a goal to mobilize \$100 billion/year by 2020 (UNFCCC 2010). The term *adaptation* is used here to refer to human activities to address the effects of climate change. Sustainable financing sources are being discussed and might include set-asides of revenues from carbon allowance auctions or from levies on the international air or maritime sectors in addition to official development assistance. Funding for climate-change adaptation is prioritized for the “most vulnerable developing countries, such as the least developed countries, small island developing States, and Africa” (UNFCCC 2010). Proposals for “ecosystem-based approaches to adaptation,” which include strategies to reduce the vulnerability of people to the effects of climate change, have been formally proposed to the UNFCCC (e.g., IUCN

2008) and compiled (UNFCCC 2011a) and are scheduled to be discussed by the UNFCCC at a workshop in 2012 (UNFCCC 2011b). These proposals include some types of forest maintenance and restoration.

## Acknowledgments

This work was partially supported by NSF DEB-0443453 to S. Andelman. We thank more than 30 conservation experts with whom we spoke in the course of this research. In particular we thank L. Rajaobelina, J. MacKinnon, J. Randrianarisoa, O. Behra, C. Holmes, J. Rabenantoandro, and J. Talbot for their assistance in Madagascar. We thank R. Hijmans for supplying future climate layers and E. Ashkenazi, D. Fischman, and J. Hewson for technical support. We thank R. Chacko, H. Campbell, S. Polasky, 3 anonymous referees, and E. Fleishman, and E. Main for useful comments on earlier versions of this manuscript.

## Supporting Information

Description of the calculation of net present values (Appendix S1), cost of minimum area for the 74 endemic species (Appendix S2), survey instrument (Appendix S3), and distribution maps for 2 example species (Appendix S4) are available online. The authors are responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

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