

# Extinction risks of Amazonian plant species

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**Estimates of the number, and preferably the identity, of species that will be threatened by land-use change and habitat loss are an invaluable tool for setting conservation priorities. Here, we use collections data and ecoregion maps to generate spatially explicit distributions for more than 40,000 vascular plant species from the Amazon basin (representing more than 80% of the estimated Amazonian plant diversity). Using the distribution maps, we then estimate the rates of habitat loss and associated extinction probabilities due to land-use changes as modeled under 2 disturbance scenarios. We predict that by 2050, human land-use practices will have reduced the habitat available to Amazonian plant species by  $\approx 12\text{--}24\%$ , resulting in 5–9% of species becoming “committed to extinction,” significantly fewer than other recent estimates. Contrary to previous studies, we find that the primary determinant of habitat loss and extinction risk is not the size of a species’ range, but rather its location. The resulting extinction risk estimates are a valuable conservation tool because they indicate not only the total percentage of Amazonian plant species threatened with extinction but also the degree to which individual species and habitats will be affected by current and future land-use changes.**

Amazon | deforestation | distributions | ecoregions | land-use changes

Ongoing development of the Amazon, including natural gas and oil production, large-scale cattle ranching, soy farming, extended networks of improved roads, and the various synergistic activities that invariably accompany increased access (fire, hunting, logging, etc.), is causing the rapid loss and degradation of natural habitat (1–6). To set conservation priorities and design appropriate mitigation strategies it is important to estimate the number, and preferably identity, of species that will be threatened by current and future land-use changes.

Several notable studies have estimated extinction risks for Amazonian plants attributable to habitat loss (7–11). These estimates have almost all been based documented or predicted changes in habitat area across the entire Amazon Basin or other comparably large regions (7–10), thereby omitting the influence of spatial patterns in species ranges and/or disturbances. By not incorporating information about the location or size of species ranges or any spatial patterns in the rates of habitat loss, the resulting extinction estimates are potentially inaccurate. Furthermore, these methods do not allow extinction risks to be calculated for individual species.

For example, Hubbell et al. (11) recently estimated the percentage of canopy trees in the Brazilian Amazon threatened with extinction by overlaying a spatially explicit map of predicted habitat disturbances over theoretical species ranges. The use of a spatially explicit disturbance map is an improvement over previous studies. However, Hubbell et al. (11) did not use spatially explicit species ranges, and instead modeled species ranges as circles (or ellipses) randomly distributed throughout the study region, thereby implicitly incorporating several unrealistic assumptions about species ranges and failing to account for pronounced and well-established spatial gradients in tree species richness (12). Tree diversity is greatest in western Amazonia and along the main stem of the Amazon River and is lowest across the large expanses of the seasonal Cerrado savannahs in southwestern Brazil (13–16). Because this is the near inverse of

the pattern predicted for future disturbances (3, 6), extinction risks were likely overestimated (12).

To accurately estimate the impacts of land-use changes, especially for the many conservation purposes in which species-specific rather than simple overall mean estimates are needed, realistic spatially explicit maps of species ranges are required. Most tropical plant species have been too poorly studied to allow for accurate range maps to be drawn from collections data alone (17). However, by incorporating other sources of data it is possible to create spatially explicit estimates of species’ potential ranges. South America has previously been subdivided into discrete “ecoregions” (18). By definition, ecoregions indicate the extent of distinct natural biological communities or areas with relatively homogeneous species composition. A plausible estimate of a species’ range is therefore the total extent of all of the ecoregions in which it is known to occur. The ecoregions occupied by plant species can be determined on the basis of herbarium collection records, and several hundreds of thousands of collection records identified to species are available online through the Global Biodiversity Information Facility (GBIF; [www.gbif.org](http://www.gbif.org)) for vascular plant species occurring within the Amazon. These records are geo-referenced and provide data on the collection coordinates, and hence known ecoregions occupied, of 40,027 species representing  $>80\%$  of the estimated 50,000 Amazonian plant species. By combining the collection localities with the maps of ecoregions, range maps can be produced for individual species that provide information not only on total area occupied but also, perhaps more importantly, range location and range shape. Although the accuracy of these ecoregion range maps will be influenced by limitations inherently associated with the use of natural history collections data (including biased geographic and taxonomic sampling, insufficient sampling of rare and/or specialist species, and geo-referencing and taxonomic errors; refs. 17, 19–22), they provide a better indication of distributions than has been used in previous attempts to estimate the extinction risks of Amazonian plant species (see *Discussion*).

Here, we use the collections data available through GBIF to map the potential ecoregion-based distributions of the more than 40,000 vascular plant species for which collections are available from the Amazon. We use these maps to estimate rates of habitat loss due to land-use changes as mapped under predictions by Soares-Filho et al. (6) of areas that will be deforested by 2050 under a “Business As Usual” (BAU) and a more optimistic “Governance” (GOV) scenario, which we have modified to extend to areas of species ranges outside the Amazon Basin (Fig. 1 and [Table S1](#)). Applying the species area curve, we translate the species-specific estimates of habitat loss into estimated extinction risks (23). The results represent a valuable tool to conservation planners because they predict not only the total

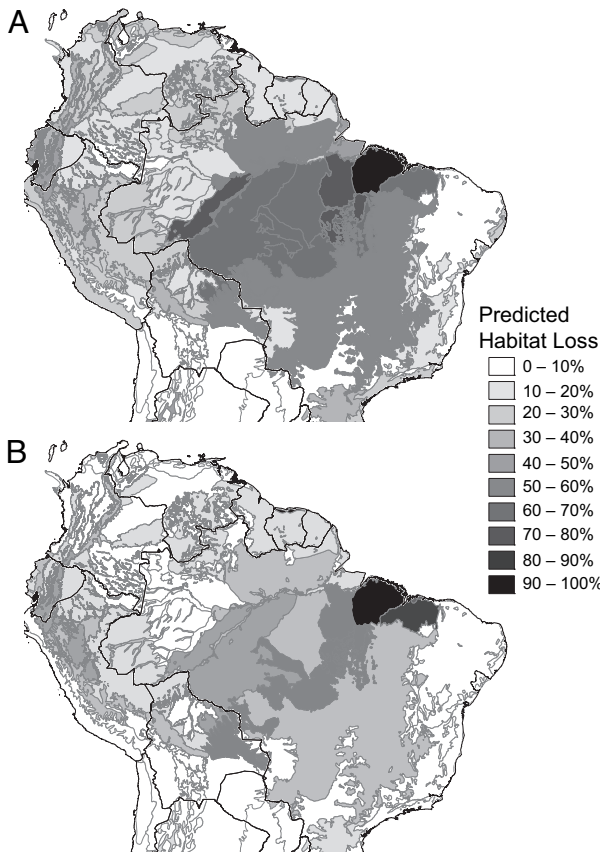
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**Fig. 1.** Percentage of habitat area predicted to be lost by 2050 per each of the 96 ecoregions inhabited by Amazonian plant species under the (A) BAU and (B) GOV land-use change scenarios modified to include ecoregions outside the Amazon Basin. See Table S1 for habitat loss estimates per ecoregion.

number of Amazonian plant species expected to eventually go extinct, but also the degree to which individual species are threatened by habitat loss.

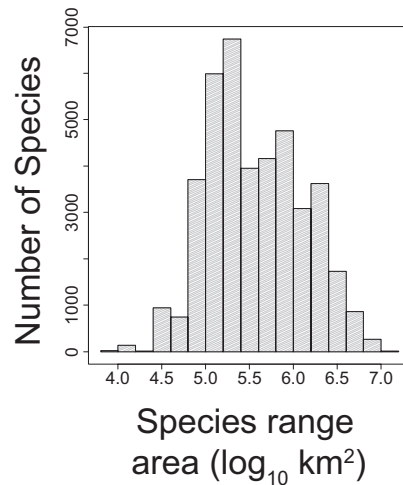
**Results**

Amazonian plant species occupy between 1 and 44 ecoregions, with the median number of ecoregions occupied being 2, resulting in an approximately log-normal distribution of range sizes, with a median range of 325,822 km<sup>2</sup> (95% confidence interval, 317,276–332,512 km<sup>2</sup>; Fig. 2 and Table S2). Overall, the undisturbed habitat area across all ecoregions available to Amazonian species is predicted to decrease by 14.6% or 29.7% by 2050 under the modified GOV and BAU scenarios, respectively. Habitat loss will vary greatly between ecoregions, from a minimum loss of <1% in some areas to a maximum habitat loss of more than 80–95% by 2050 in the Tocantins/Pindare moist forests in eastern Brazil (Fig. 1 and Table S1).

By combining the spatially explicit range maps and disturbance predictions, we estimate that by 2050, land-use changes will have caused species ranges to decrease in area by an average of 17.3% (17.3–17.5%) or 30.4% (30.3–30.6%); Fig. 3 and Table S2). Applying the species–area relationship with  $z = 0.25$  to the changes in habitat area, we estimate that the per-species extinction risks of the 40,027 Amazonian plants included in our analyses average 4.8% (4.7–4.8%) and 9.1% (9.0–9.1%) under our GOV and BAU disturbance scenarios, respectively (Fig. 3 and Table S2).

**Discussion**

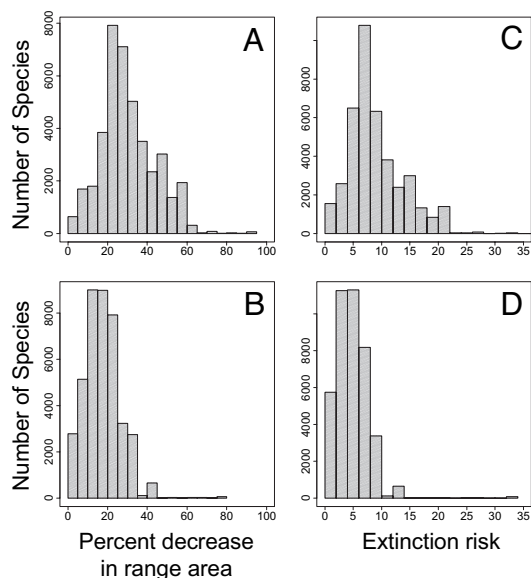
According to our estimates, the overriding determinant of habitat loss and extinction risk for Amazonian plant species is



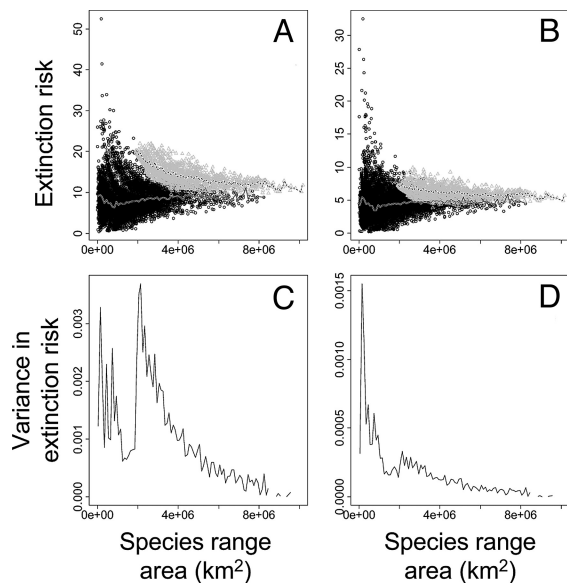
**Fig. 2.** The distribution of estimated range areas (log<sub>10</sub> scale) for the >40,000 vascular plant species for which collection data are available from the Amazon. See Table S2 for range area estimates per species.

geographic location. This is exemplified by the fact that species whose ranges include the Cerrado are predicted to be at much greater risk of extinction than species whose ranges fall entirely outside the Cerrado (Fig. 4). On average, extinction risks are ~50% greater for Cerrado vs. non-Cerrado species with similar range areas under either the BAU or the GOV scenario (Fig. 4). There are several reasons to believe that the true disparity in extinction risks between Cerrado and non-Cerrado species may be even greater.

Based on the conversion of natural habitat to agricultural or pastoral land over the past 3 decades, we applied a habitat loss rate to the Cerrado ecoregion of 1.5% yr<sup>-1</sup> (see Methods and ref. 24). However, in our model, habitat loss was only calculated for 2000–2050, and thus we did not include any of the more than 30 million hectares of Cerrado that had already been converted. Furthermore, habitat loss in the Cerrado has actually acceler-



**Fig. 3.** The percent reduction in species range areas under the modified BAU and GOV land-use change scenarios (A and B, respectively) and associated extinction risks (C and D, respectively). See Table S2 for habitat loss and extinction risk estimates per species.



**Fig. 4.** Extinction risk and variation in extinction risk of Amazonian plant species vs. range area. (A and B) Estimated extinction risk vs. original range area under the BAU (A) and GOV (B) land-use change scenarios. Gray triangles indicate species whose ranges include at least in part the Cerrado ecoregion of southwestern Brazil; black points indicate all other species whose ranges do not include the Cerrado. Lines show average extinction risks for binned range sizes of Cerrado (dashed line) and non-Cerrado species (bin width = 100,000 km<sup>2</sup>). (C and D) The variation in extinction risk estimates for species within the binned range areas as based on the BAU (C) and GOV (D) land-use change scenarios. The peak in variation at range size =  $\approx 2,000,000$  km<sup>2</sup> is due to the entrance of Cerrado species.

ated to 3.1–4.3% yr<sup>-1</sup> (22,000–30,000 km<sup>2</sup>·yr<sup>-1</sup>) of natural habitat (24). If we include historic habitat loss and use a contemporary habitat loss rate of 3.7%, extinction risk for Cerrado species rises to >2 times greater than for non-Cerrado species.

Another indication of the importance of range location is the large increase in the variation of species' extinction risk estimates with decreasing range size, such that variation in extinction risk is greatest for habitat specialists occupying just one to a few ecoregions and having correspondingly small range sizes (Fig. 4). The reason for the high degree of variation in small-ranged species is intuitive; some small-ranged habitat specialists will occur largely or entirely within areas with relatively low rates of habitat loss, whereas other small-ranged species will occur just in the areas of heaviest disturbance. In contrast, widespread habitat generalists, by the very fact that they have large ranges, will experience habitat loss at rates approaching the Amazonian average. It is important to note that although many habitat specialists or small-ranged species may not be threatened by the habitat loss predicted in the disturbance maps used here, these species are fundamentally at greater risk of extinction because any loss in habitat area will consume a larger proportion of their ranges (25). Many of the small-ranged species that currently appear "safe" may, therefore, still be highly vulnerable to extinction from other development projects and/or localized disturbances.

Contrary to previous studies (e.g., ref. 11), we did not find a decrease in extinction risk with increasing range/population size. Extinction risk was greater, on average, for large-ranged species than for small-ranged ones. This relationship is driven by the disproportionately high risk of extinction for Cerrado species. The Cerrado is the largest Amazonian ecoregion ( $\approx 2,000,000$  km<sup>2</sup>), and thus species recorded from there all have relatively

large ranges. If Cerrado species are excluded, there is a slight decrease in extinction risk with increasing range size, but less than 0.5% of the variation in extinction risk is explained by range size under either disturbance scenario (Fig. 4).

Overall, we estimate that by 2050,  $\approx 5\%$  or  $9\%$  of all Amazonian plant species will be threatened with eventual extinction because of land-use changes and associated habitat loss (Fig. 3 and Table S2). No species is predicted to lose its entire habitat area, and thus these extinctions will not be immediate. Rather, we anticipate that current and future land-use changes will create an extinction debt in which species loss occurs gradually over several decades to centuries (27). The actual rate at which individual species will go extinct will vary depending on many factors, including the fine-scale spatial pattern of habitat loss as well as the ecological characteristics of the species (27). As a few examples, other factors being equal, species whose ranges become subdivided into small, isolated fragments are predicted to go extinct faster than species left with large, continuous patches of habitat (ref. 23, but see ref. 28); short-lived annual plants are expected to go extinct faster than long-lived perennials or trees; and species that depend on strict mutualistic relationships with other organisms (e.g., animal pollinators or seed dispersers) are expected to go extinct faster than "generalists." During the lag between disturbance and extinction, the fate of species may be altered for better or for worse by factors such as conservation efforts, changes in land-use practices, species interactions, or the influence of human disturbances other than land-use changes, such as climate change and introduced species.

The proportion of Amazonian species that we predict to be threatened with extinction because of land-use changes is markedly less than the 20% and 33% predicted under the "middle of the road" extinction model with optimistic and pessimistic deforestation scenarios, respectively, by Hubbell et al. (11). One possible reason for the difference is that Hubbell et al. (11) looked at just canopy trees, whereas we included all vascular plant species for which there were available collections data. However, we do not believe this to be the case, because there is no reason to expect that extinction risks will differ systematically between life forms, especially as estimates were based only on predicted changes in range size and did not incorporate any physiological or ecological responses to disturbance (the actual times to extinction may be expected to differ; see above). If anything, applying our model to just canopy trees would likely decrease estimates of overall extinction risk even further. This is because extinction risks were elevated in the savannahs of the Brazilian Cerrado, which support fewer tree species than the relatively undisturbed forests of the western Amazon (14, 15). Another difference between our methods is that Hubbell et al. (11) artificially confined species ranges to within the geopolitical borders of the Brazilian Amazon. The vast majority of Amazonian species have ranges that extend beyond the Brazilian Amazon, and thus they will not face certain extinction even if facing a total loss of habitat within that region, especially because habitat loss is generally slower in ecoregions outside the Brazilian Amazon (Fig. 1 and Table S1). That limiting species ranges can overestimate extinctions has been well demonstrated, specifically for birds in eastern North America (29). In a more direct comparison, if we truncate species ranges to just the Brazilian Amazon and use the same predicted disturbance maps (3) as Hubbell et al. (11) but still incorporate our spatially explicit range maps, our estimates of mean extinction risks do, in fact, increase, but only to 17% and 22%. However, if we also use the same habitat-loss-to-extinction transformation as used by Hubbell et al. (11), we estimate zero extinctions, because no species is predicted to lose all of its habitat (Fig. 3, Table S1, and Table S2). It is important to note that unlike the Soares-Filho et al. (6) disturbance map used in our estimates, the disturbance map used by Hubbell et al. (11) does not distinguish between nonforest and

deforested areas (3), and thus may be inappropriate for estimating rates of habitat conversion.

A central motivation of our study was to reduce the number of unrealistic assumptions that have potentially weakened previous estimates of Amazonian extinction rates (12); however, many important caveats remain. Namely, although we contend that estimating species' distributions based on the occurrence of collections within ecoregions produces range maps that are more informative than those used in previous studies, there are many factors that may limit their accuracy. Range maps based on the locations of herbarium collections are potentially misleading because of inaccuracies in geo-referencing and/or taxonomy (21, 22). Geo-referencing errors may cause significant errors in estimates of species ranges because ranges are based on the presence/absence of species within defined ecoregions. Species ranges will be overestimated if collections are listed as occurring in ecoregions where the species does not actually occur (or, conversely, underestimated if species are listed as not occurring in regions where they do occur). However, because only presence/absence within ecoregions is counted, the majority of geo-referencing errors will likely not cause any change in species ranges at all.

Perhaps even more critical is the simple paucity of collections data for most tropical plant species (17). The total plant diversity of the Amazon Basin has been estimated to be as high as 50,000 species, but only 40,000 of these species are represented by even a single available collection record in GBIF. It is likely that the unrepresented species are disproportionately rare and/or habitat specialists. Although these species may therefore be inherently more sensitive to habitat loss, their fate will ultimately depend largely on where they occur in relation to disturbance as we discuss above. Many of the unrepresented species likely come from undercollected areas or habitats. There are many potential causes for undercollecting, but one of the foremost is restricted access. Limited access may also slow or hinder future land-use changes, thereby reducing the danger to any species occurring in these areas.

Many of the species that are included here are represented by only a very small number of collections, which may limit our ability to accurately map their distributions. "Undercollected" species may not be counted as occurring in some ecoregions where they truly occur, resulting in underestimates of species ranges, with subsequent impacts on estimates of habitat loss and extinction risk. An example of how undercollecting may have an impact on extinction estimates comes from the Juruá-Purus moist forest ecoregion in Brazil. Fewer than 100 collections representing 82 plant species are currently available through GBIF for this ecoregion, despite its large area ( $\approx 250,000$  km<sup>2</sup>) and predicted high biodiversity (16, 18). According to modeled land-use change scenarios, this ecoregion will receive relatively little impact (Fig. 1 and Table S1) (3, 6), and thus intensifying collection/digitizing efforts and expanding the represented list of species will almost certainly have the effect of lowering estimates of the habitat loss and extinction risks. Conversely, if species lists are expanded for more disturbed but undercollected ecoregions, such as the Monte Alegre varzea of Brazil ( $\approx 66,000$  km<sup>2</sup>, with just 107 collections representing 95 species), which is predicted to lose between a quarter and a half of its natural habitat area over the same period (3, 6), extinction estimates will increase. Errors such as these may potentially be avoided by applying criteria for the minimum number of collections per species, but this could itself potentially skew extinction risk estimates by disproportionately excluding rarer species. The impacts of undercollecting will be minimized by the use of presence/absence per ecoregion, because only a single collection is required per species per ecoregion occupied.

Although the counting of ecoregions may help minimize some errors, it may itself result in large overestimates of species ranges

if species are actually confined to smaller areas or habitats within the ecoregions. Although this is likely to be true for many species, we contend that ecoregions are fair estimates of potential ranges. Extinction estimates based on loss of area within ecoregions thus implicitly incorporate the assumption that species currently confined to smaller areas will be capable of migrating within their potential ranges. If species are incapable of migrating, or if the pace of habitat destruction exceeds migration capabilities, then the use of ecoregions may underestimate extinction risks for some species. Conversely, extinction risks will be overestimated if species occur predominantly within just the undisturbed areas within ecoregions.

To further improve the accuracy of range maps, it will be necessary to increase the quality and quantity of collections data. Improved/augmented collection records will not only allow for better estimates of which species occur in which ecoregions, but will also allow for finer-scale mapping; for example, by using bioclimatic niche or envelope models. Despite the potential inaccuracies, species ranges based on even sparse collections data and coarse habitat/ecoregion maps are a significant improvement over previous studies, which have either assumed all species to be distributed everywhere (i.e., as when overall extinction rates are estimated based on average rates of habitat loss across the entire region) or that species range sizes are a direct translation of abundance estimates and randomly distributed (as in ref. 11).

In addition to the problems arising from using collections data and ecoregions, we based our estimates of extinction probabilities on changes in habitat area predicted over the next several decades (which itself may be erroneous, especially for areas outside the Brazilian Amazon for which overall country-wide estimates were used) and the relationship between area and species richness. The many potential problems with extrapolating extinction risk from change in habitat area have been explored in depth elsewhere (30–36) and will not be discussed further here.

Our estimates of extinction risks are based only on habitat loss and do not include other possible causes, such as other synergistic human disturbances (e.g. fire, logging, climate change) or disruptions of biological interactions (e.g., trophic cascades). We and others have demonstrated previously that the effects of distorted biological interactions may be even stronger drivers of species loss from disturbed tropical forests than the direct effects of habitat reduction (37, 38). Nor did we incorporate effects of future climate change into our analyses. Climate change will threaten many Amazonian plant species through a variety of mechanisms, including shifted distributions of climatically suitable habitats (39). The ability of species to respond to changing climates will be diminished in a context of land-use change (e.g., migration corridors may be cut), increasing the number of species that would be threatened by either climate change or land-use change alone.

Finally, in estimating changes in species ranges, we only considered the loss of natural habitat area and did not allow for any successional regrowth or habitat recovery. If secondary habitats are able to support species that would otherwise be threatened, loss of habitat area will be slowed and extinction risks decreased (40).

Despite these caveats and the associated uncertainties, this study represents an important advancement in estimating extinction risks of tropical plant species. As discussed above, to further refine extinction rate estimates it will be necessary to improve the quality, quantity, and availability of collections data. Additionally, estimates will benefit from improved predictions of habitat disturbance and recovery rates (both in and out of the Amazon) and, perhaps most importantly, increased understandings of the various and complex ways in which species will respond to different forms and degrees of human disturbances.

## Conclusions

We predict that  $\approx 5\text{--}9\%$  of the more than 40,000 Amazonian plant species studied here will become committed to extinction by 2050 because of land-use changes and habitat loss. Although the number of threatened species is less than estimated in some previous studies, we stress that ongoing and future land-use changes pose serious threats to Amazonian biodiversity. If the risk estimates from this study are applied to the 50,000 total vascular plant species (12,500 canopy trees; ref. 11) estimated to occur in the Amazon Basin, we predict that between 2,400 and 4,550 species (600–1,138 species of trees) will become committed to extinction over the next several decades because of land-use change alone. This is an unacceptable loss rate and calls for strong and immediate conservation actions. Beyond estimates of just overall or mean extinction risks, we estimate habitat loss and extinction risks individually for nearly 80% of all Amazonian plant species (Table S2). Likewise, we have produced estimates of habitat loss rates for individual ecoregions (Table S1), which can themselves be extrapolated to rates of local species loss. By using these data, conservation efforts can be directed with greater precision at the specific plant species or plant communities most threatened by future land-use changes. For example, it is clear from our results that the species most immediately threatened with extinction are those occurring in the Cerrado and the surrounding ecoregions (Figs. 1 and 4 and Table S1), and thus we implore that conservation efforts there be expanded.

## Methods

**Species Range Maps.** To create species ranges, we downloaded all herbarium records for vascular plant specimens collected from tropical South America available through the GBIF ([www.gbif.org](http://www.gbif.org); only records identified to species and containing geographical coordinates were used in the analysis, and data were screened according to standard protocol; Table S3). We then mapped the ranges for each of the 40,027 species collected from the Amazon basin as the total extent of all ecoregions (18) in South America from which the species had been collected. The mapped species ranges included areas outside the Amazon basin, for a total of 96 ecoregions represented.

**Changes in Habitat Area.** We estimated the area of habitat loss within the forested regions of the Amazon (i.e., all Amazonian ecoregions except the

Beni Savanna, the Cerrado, and the Guianan Savanna) by overlaying the Soares-Filho et al. (6) map of areas predicted to be deforested by 2050 under both a BAU and a more optimistic GOV scenario. The GOV model predicts patterns of deforestation under the assumption of increasing protection, and hence decreasing habitat conversion rates.

Because detailed, spatially explicit predictions of future land-use changes are lacking for most areas outside the Amazon Basin, we estimated the amount of habitat loss for each non-Amazonian ecoregion, or portion of ecoregions falling outside the Amazon, based on the annual rates of deforestation recorded for natural forested areas in the encompassing country between 1990 and 2000 [as estimated by the Food and Agriculture Organization of the United Nations (42)] applied over a period of 60 years. A period of 60 years was chosen to encompass both the loss of habitat from 1990 to 2000 and the predicted loss of habitat by 2050. In our BAU scenario, we maintained a constant rate of habitat loss over the 60-year period. In our GOV scenario, we decreased the rate of habitat loss by 10% annually for the period from 2000 to 2050. Finally, we applied specific estimates of habitat loss for the Cerrado, because this area is being lost at a disproportionately high rate because of intensive conversion to agriculture (primarily cattle ranches and soy plantations). In our BAU scenario, habitat in the Cerrado was lost at a constant rate of 1.5% per year (24). In the GOV scenario, we decreased the rate of habitat loss in the Cerrado by 10% annually for the period 2000–2050 (to a minimum habitat loss of  $<0.003\%$  per year; Fig. 1).

We predicted the decrease in range area for each individual species ( $\Delta A$ ) as the summed area lost in all occupied ecoregions. By using the species-specific estimates, we calculated the mean percent reductions in range size and 95% confidence intervals based on 10,000 bootstrap estimates.

**Species Extinction Risks.** We estimated the extinction risk ( $E$ ) for each individual plant species based on estimates of the original range size ( $A_1$ ) and range size after disturbance ( $A_2 = A_1 - \Delta A$ ) and the relationship between habitat area and species richness according to the species–area relationship (23), such that that  $E = 1 - (A_2/A_1)^z$ . We assumed  $z = 0.25$  to be consistent with other studies and facilitate cross-comparisons with previous estimates (e.g., refs. 7, 8, 10). Higher values of  $z$  will result in greater extinction risks, and lower  $z$  values will decrease estimates of extinction risks (23). As above, we used the species-specific risk estimates to calculate the mean extinction risk across all species with 95% confidence intervals.

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