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Toward quantification of the impact of 21st-century deforestation on the extinction risk of terrestrial vertebrates

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Abstract: *Conservation actions need to be prioritized, often taking into account species' extinction risk. The International Union for Conservation of Nature (IUCN) Red List provides an accepted, objective framework for the assessment of extinction risk. Assessments based on data collected in the field are the best option, but the field data to base these on are often limited. Information collected through remote sensing can be used in place of field data to inform assessments. Forests are perhaps the best-studied land-cover type for use of remote-sensing data. Using an open-access 30-m resolution map of tree cover and its change between 2000 and 2012, we assessed the extent of forest cover and loss within the distributions of 11,186 forest-dependent amphibians, birds, and mammals worldwide. For 16 species, forest loss resulted in an elevated extinction risk under red-list criterion A, owing to inferred rapid population declines. This number increased to 23 when data-deficient species (i.e., those with insufficient information for evaluation) were included. Under red-list criterion B2, 484 species (855 when data-deficient species were included) were considered at elevated extinction risk, owing to restricted areas of occupancy resulting from little forest cover remaining within their ranges. The proportion of species of conservation concern would increase by 32.8% for amphibians, 15.1% for birds, and 24.7% for mammals if our suggested uplistings are accepted. Central America, the Northern Andes, Madagascar, the Eastern Arc forests in Africa, and the islands of Southeast Asia are hotspots for these species. Our results illustrate the utility of satellite imagery for global extinction-risk assessment and measurement of progress toward international environmental agreement targets.*

Keywords: conservation prioritization, forest loss, habitat loss, IUCN Red List, remote sensing, species conservation

Hacia la Cuantificación del Impacto de la Deforestación del Siglo XXI sobre el Riesgo de Extinción de los Vertebrados Terrestres

Resumen: *Las acciones de conservación necesitan ser priorizadas, considerando con frecuencia el riesgo de extinción de las especies. La Lista Roja de la Unión Internacional para la Conservación de la Naturaleza (UICN) proporciona un marco de trabajo objetivo y aceptado para la valoración del riesgo de extinción.*

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Las valoraciones basadas en los datos colectados en el campo son la mejor opción, pero los datos de campo sobre los cuales basar las valoraciones con frecuencia son limitados. Los datos colectados por medio de la teledetección pueden usarse en lugar de los datos de campo para informar a las valoraciones. Los bosques tal vez sean el tipo de cubierta de suelo mejor estudiado para el uso de datos de teledetección. Con un mapa de acceso abierto y resolución de 30-m de la cobertura de árboles y su cambio entre 2000 y 2012, valoramos la extensión de la cobertura de bosque y la pérdida dentro de las distribuciones de 11, 186 especies de anfibios, aves y mamíferos dependientes del bosque a nivel mundial. Para 16 especies, la pérdida del bosque resultó en un riesgo de extinción elevado, bajo el criterio A de la lista roja, debido a las declinaciones rápidas de población inferidas. Este número incrementó a 23 cuando las especies con deficiencia de datos (es decir, aquellas con información insuficiente para su evaluación) fueron incluidas. Bajo el criterio B2 de la lista roja, 484 especies (855 cuando se incluyeron las especies con deficiencia de datos) se consideraron con riesgo alto de extinción, debido a las áreas restringidas de ocupación como resultado de la pequeña cobertura del bosque que permanece dentro de su distribución. La proporción de especies de interés para la conservación incrementaría en 32.8 % para los anfibios, 15.1 % para las aves y 24.7 % para los mamíferos si nuestros cambios de categoría sugeridos son aceptados. América Central, los Andes del norte, Madagascar, los bosques del Arco Oriental de África y las islas del sureste asiático son puntos clave para estas especies. Nuestros resultados ilustran la utilidad de las imágenes satelitales para la valoración global de la extinción de riesgo y para la medición del progreso hacia los objetivos de los acuerdos ambientales internacionales.

Palabras Clave: conservación de especies, Lista Roja UICN, pérdida de bosques, pérdida de hábitat, priorización de la conservación, teledetección

Introduction

The IUCN Red List categorizes species according to their risk of extinction (IUCN 2014). It has become a valuable source of information for the conservation planning process and has increasingly helped to focus priorities for conservation funding and action (Rodrigues et al. 2006). The red-list data also underpin the IUCN Red List Index (RLI), an indicator of temporal trends in extinction risk (Butchart et al. 2004, 2007). The IUCN uses 5 criteria with quantitative thresholds to assign species to 1 of 7 hierarchical categories in increasing order of extinction risk from least concern to extinct (IUCN 2014). These criteria are based on rates of population decline (criterion A), distribution size, structure, and trends (criterion B), population size, structure, and trends (criterion C), absolute population or distribution size (criterion D), and modeled extinction probability (criterion E). Species in the 3 categories of critically endangered, endangered, and vulnerable are collectively referred to as threatened. These species and those in the category near threatened are referred to as being of conservation concern. The remaining categories are least concern, extinct, data deficient, and not evaluated. The IUCN Red List system is designed to take into account uncertainty and allows the use of inference where appropriate (Akçakaya et al. 2000; IUCN 2014). For example, if quantitative data on population trends are not available from field surveys, it is acceptable to infer them from rates of habitat loss.

Forests hold the highest levels of species diversity (e.g., Hilton-Taylor et al. 2009), and forest loss (principally driven by agriculture and logging) is considered one of the top threats to biodiversity (Pimm et al. 1995; Bailie et al. 2004). Objective estimates of forest loss can be produced through remote sensing, making it possible to determine rates of loss over time and special extents on local to global scales (e.g., Achard et al. 2002; Hansen et al. 2010; Hansen et al. 2013). Forest-loss data derived from remote sensing have been used to inform extinction-risk assessment at local to regional scales, for which rates of forest loss are used as surrogates for population declines under red-list criterion A (e.g. Buchanan et al. 2008) and the calculation of area of occupancy under criterion B (Hall et al. 2009). Such approaches have generally been restricted to particular taxa, countries, or regions because the analyses are computationally intensive and appropriate standardized land-cover change data sets have not been available at a global scale. Hansen et al. (2013) produced a global map of tree cover change from 2000 to 2012, mapping tree-cover loss and gain from remote sensing data across the entire globe at a 30-m resolution.

Here, we combined remotely sensed data on land-cover change with species' distribution ranges derived from IUCN Red List polygon maps (BirdLife International & NatureServe 2014; IUCN 2014) for forest-dependent amphibians, birds, and mammals. This allowed us to infer rates of habitat loss in a standardized way for >11,000 species worldwide. We applied IUCN Red List criteria to these data to identify the number of species potentially qualifying for uplisting to higher categories of extinction risk. We based our assessment on rates of population decline (criterion A), inferred from forest loss, and areas of occupancy (AOO) (criterion B2), inferred from remaining forest cover. We used extent of forest within species' elevational limits and geographical range (i.e., extent of suitable habitat) (Beresford et al. 2011; Buchanan et al. 2011; Rondinini et al. 2011) as a maximum potential value for AOO. We described the geographical distributions of the species that potentially qualify for uplisting and identified areas holding the largest numbers of species threatened by deforestation. Finally, we identified areas in which the analysis could be improved in the future to maximize the benefits derived from remote sensing for assessments of species' conservation status.

Methods

Species Data

We extracted species distribution polygons for forest-dependent amphibians (3540 species; IUCN 2014), birds (6283 species; BirdLife International & NatureServe 2014), and mammals (1363 species [IUCN 2014]) (Fig. 1 & Supporting Information). These vector polygons delimitated the current known ranges for each species (either within range or not in range). Forest-dependent bird species were defined as those having high dependency or medium dependency (Buchanan et al. 2008; Bird et al. 2012). Species with high dependency are characteristic of the interior of undisturbed forest; they may persist in secondary forest and forest patches if their particular ecological requirements are met, but breed almost invariably within forest. Species with medium dependency may occur in undisturbed forest but are also found in forest strips, edges, and gaps and typically breed within forest (BirdLife International 2015). For amphibians and mammals, we considered forest specialists those that have a high dependency on forests (Rondinini et al. 2011; Ficetola et al. 2015). These species are characteristic of the interior of undisturbed forest; they may persist in secondary forest and forest patches if their particular ecological requirements are met, but they breed almost invariably within forest.

We used distribution polygons with presence coded as extant or probably extant and origin coded as native or reintroduced. We extracted data on altitude preferences and generation lengths (Schad 2008; Rondinini et al. 2011; Pacifici et al. 2013; IUCN 2014; BirdLife International 2015; Ficetola et al. 2015). We defined generation length as "the average age of parents of the current cohort (i.e. newborn individuals in the population)"; generation length, therefore, reflects the turnover rate of breeding individuals in a population (IUCN 2001). Altitude limits were not known for 18% of amphibians, 22% of birds, and 50% of mammals. In these cases, we used the minimum and maximum values within the species range (Beresford et al. 2011; Rondinini et al. 2011).

Forest Cover Data

Tree cover data (hereafter forest cover) were extracted from the Hansen et al. (2013) global forest change (GFC) map (Fig. 1). This 30-m resolution map was derived from Landsat imagery and made available via the Google Earth Engine (https://earthengine.google.org/). The treecover2000 layer represents the percent forest cover in the year 2000, and the lossyear layer reports for each pixel the year when a deforestation event occurred (i.e., forest loss of sufficient magnitude to be detected as a loss by the Hansen et al. [2013] algorithm) from 2001 to 2012.

The GFC map cannot always distinguish between plantations and natural forest (Tropek et al. 2014). Consequently, we excluded known wood fiber plantations, oil-palm plantations, and logging areas for which data were available from our analyses. These data, obtained through The World Resources Institute (2014), were limited to Cameroon, Canada, Central African Republic, Democratic Republic of the Congo, Equatorial Guinea, Gabon, Indonesia, Liberia, and Republic of the Congo. They covered 3 million km^2. The plantations covered approximately 20% of tree cover in the countries for which these data were available, indicating the forested area we estimated for each species may have resulted in an underestimated extinction risk.

A comparison of the Hansen et al. (2013) global data with a visual-assessment study indicated there was a 4% difference in tree-cover estimates globally (Achard et al. 2014). However, there was a 22% difference in Africa; cover estimated through the Hansen et al. algorithm was lower than the visual assessment in this area (Achard et al. 2014). Accuracy depended on how forest was defined, highlighting the difficulty of comparisons between data (Achard et al. 2014), not to mention uncertainty in the accuracy of both classifications.

Analyses

We used a Python 2.7 programming interface. We imported species distribution polygons into Google Earth Engine as raster images. Taking each species in turn, we used the GTOPO30 digital elevation model with a resolution of 30 arc seconds (approximately 900 m at the equator) to remove areas within each species' distribution that fell outside its altitude range. The extent of species ranges was further reduced to only those areas considered habitat in 2000 based on the treecover2000 layer in the GFC map. This was equivalent to an estimate of the extent of suitable habitat (ESH). Forest loss from 2001 to 2012 was obtained by summing the area of all pixels that indicated loss from 2001 to 2012 (from the lossyear layer in the GFC map). With this calculation, we assumed all the original tree cover (from the treecover2000 layer) within the pixel was lost. For instance, if the pixel's value in the treecover2000 layer was 70% and it was marked in the lossyear layer in 2005, we assumed 70% loss by 2012.

Forest cover remaining in 2012 was an estimate maximum possible AOO (actual AOO would be less than this because species do not occupy their habitat entirely). The

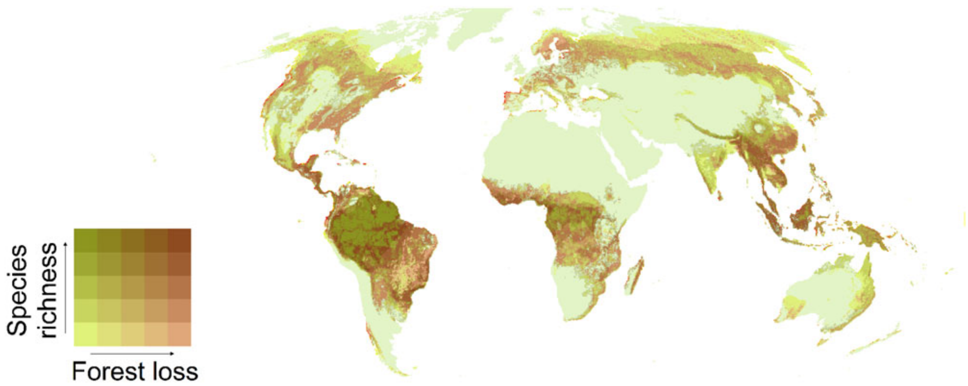

Figure 1. Number of forest species and percent loss of forest from 2000 to 2012. Both axes are divided into quintiles.

accuracy of ESH maps is likely to vary globally, and the limitations and advantages of such types of spatial layers are known (e.g., Beresford et al. 2011; Rodrigues 2011). Because it is recommended that AOO be measured at a 2 × 2 km spatial resolution for red-list assessments (IUCN 2012), the forest cover and loss maps were first rescaled to match this resolution. That is, we measured total forest cover and loss in each 4 km^2 pixel. This may have resulted in the loss of spatial detail where distributions are well known and given a false accuracy for species whose distributions are less well understood. For migratory birds, we assessed forest loss and remaining forest cover within the resident + breeding distribution and separately within the resident + nonbreeding distribution. We used the lower value of forest cover as the maximum possible AOO and the highest value of forest loss. Full code is available through GitHub, a web-based code repository hosting service (https://github.com/RSPB/GFCalculator).

IUCN Red List Assessment

Under the IUCN Red List, each species is assessed against all criteria and is listed at the highest category met under any of them (IUCN 2001). The implication of the forest-loss data for each species' IUCN Red List assessment was evaluated by trained assessors from the designated red-list authorities or assessment-coordination units for each of the taxa we considered. We applied forest-loss estimates to red-list criterion A2, which is used to assess extinction risk based on population decline over the past 3 generations or 10 years (whichever period is longer [i.e., 30 years for a species with generation time of 10 years or 10 years for a species with generation time of 2 years]). This follows IUCN guidance. We assumed the rate of population change is equal to that of forest loss (i.e., the loss of 15% cover will result in a 15% decrease in the population as 100 × [1 – (forest loss$^{(\text{generation length}/12)}$)]. This approach follows the IUCN criteria and has been used in previous analyses (Buchanan et al. 2008; Bird et al. 2012), although the relationship may be nonlinear for some species (e.g., Bender et al. 1998).

The red-list category near threatened does not have specified thresholds, but following guidelines from IUCN (2012), we assumed that any species with a decline of >25% over 10 years or 3 generations would qualify as near threatened. We examined all species with forest loss rates close to a category threshold (10% distance from a given threshold) and identified (from documentation in current red-list assessments or from the literature) those for which hunting pressures or other threats were likely to be sufficiently severe for the overall population decline to exceed the relevant category threshold under criterion A2. Thus, a species facing a forest loss rate of 40% in 3 generations qualified as vulnerable (category threshold: population decline rate ≥30% and <50% over 10 years or 3 generations) owing to forest loss alone but could qualify as endangered (population decline rate ≥50% and <80% over 10 years or 3 generations) if additional factors would likely drive severe declines (e.g., intense hunting pressure). For many amphibian species, generation length is unknown; therefore, we assessed extinction risk over 10 years, following IUCN (2012). We also applied the maximum possible AOO estimate (inferred from forest-cover data for 2012) to IUCN Red List criterion B2, which is used to assess extinction risk on the basis of restricted AOO.

To qualify as threatened under criterion B2, species must have an AOO estimate below a specified areal threshold (10 km^2 for critically endangered, 500 km^2 for endangered, and 2000 km^2 for vulnerable) and meet 2 of 3 subcriteria (a, b, or c). Subcriterion a requires the distribution to be severely fragmented or restricted to fewer than a specified number of locations (IUCN 2012). Subcriterion b requires a continuing decline in population or distribution, which we assumed to be the case for those species for which our data showed a decline in forest cover from 2000 to 2012. Subcriterion c requires species to be undergoing extreme fluctuations in population size or distribution. We did not consider subcriterion c here because our focus was forest cover from 2000 to 2012, a timespan that does not allow for rapid fluctuations in cover. We assumed those species with AOO estimates below the relevant category threshold and that are also undergoing a decline would also qualify under subcriterion a on fragmentation. This was

Table 1. Species that potentially qualify for a higher International Union for Conservation of Nature (IUCN) Red List threat category based on forest loss in their ranges between 2000 and 2012.[a]

Class	*Species[a]*	*Current red-list category[b]*	*Current red-list criteria*	*Proposed category under A2*	*Forest cover 2000 (km^2)*	*Forest loss 2000–2012 (km^2)*	*Trend period (3 generations or 10 years)*	*Forest loss in 3 generations or 10 years (%)*
Amp.	*Bufo wolongensis*	DD		VU	19.4	10	10	46.88
Amp.	*Dendropsophus coffeus*	LC		VU	10.1	4	10	30.26
Amp.	*Eupsophus septentrionalis*	DD		VU	197.2	83	10	36.75
Amp.	*Meristogenys macrophthalmus*	DD		VU	526.6	241	10	40
Amp.	*Ambystoma talpoideum*	LC		VU	383168.2	56121.5	10	24.21
Amp.	*Atelopus sanjosei*	DD		NT	302.5	53	18	25.25
Amp.	*Rhacophorus gadingensis*	DD		NT	31.9	11	10	28.51
Bird	*Rhinoplax vigil* #	NT	A2,3,4	EN	643050.9	78256	19.8	24.59
Bird	*Malurus pulcherrimus*	LC		VU	28011.9	5736	21	33.03
Bird	*Psittacula longicauda*	NT	A2,3,4	VU	410509.2	71411	24.6	32.41
Bird	*Rhabdotorrhinus corrugates*	NT	A2,3,4	VU	119211.5	21796	26.1	35.54
Bird	*Bubo sumatranus*	LC		NT	765808.4	93446	27.9	26.11
Bird	*Columba trocaz* #	LC		NT	17.2	3.52	16.8	20.96
Bird	*Rhaphidura leucopygialis* #	LC		NT	616329.3	88721.8	21.6	21.1
Bird	*Strix chacoensis* #	LC		NT	199451.1	24498.8	28.8	22.8
Bird	*Anorrhinus galeritus* #	LC		NT	783758.9	94214.5	29.4	23.83
Bird	*Anthracoceros malayanus* #	LC		NT	293183.2	52919.8	27.6	21.64
Bird	*Micrastur mintoni* #	LC		NT	1536539	126286	25.8	21.85
Bird	*Amazona xantholora* #	LC		NT	72538.6	6119.7	12.3	23.91
Bird	*Climacteris rufus* #	LC		NT	37655.7	5222.1	21.3	20.95
Bird	*Macronous ptilosus* #	LC		NT	221215.4	41898.9	11.7	20.21
Mam.	*Petinomys hageni*	DD		EN	5.5	4	11.4	67.15
Mam.	*Diomys crumpi*	DD		VU	5.6	3	10	43.88

[a]*Species for which forest loss in 3 generations or 10 years was <10% lower than a given red-list category threshold and for which # rate of population decline was inferred to exceed the threshold owing to hunting (#) or species for which the rate of population decline was inferred to exceed the threshold owing to predation by invasive non-native species (*).*
[b]*Abbreviations: DD, data deficient; LC, least concern; NT, near threatened; VU, vulnerable; EN, endangered; CR, critically endangered.*

Table 2. Number of forest-dependent species potentially qualifying for a higher International Union for Conservation of Nature (IUCN) Red List threat category under IUCN criterion A2 from among species listed in Table 1.[a]

	Amphibian					*Bird*					*Mammal*				
	proposed category					*proposed category*					*proposed category*				
current category	*CR*	*EN*	*VU*	*NT*	*current total*	*CR*	*EN*	*VU*	*NT*	*current total*	*CR*	*EN*	*VU*	*NT*	*current total*
CR					241					137					86
EN					511					293					192
VU					455					519					1144
NT					285		1	2		714					98
LC			2		1350			1	10	4592					532
DD			3[b]	2[a]	698[b]					28[b]		1[b]	1[b]		285[b]
Uplisted			2, 5[b]	2[b]			1	3	10			1[b]	1[b]		

[a]*Abbreviations: DD, data deficient; LC, least concern; NT, near threatened; VU, vulnerable; EN, endangered; CR, critically endangered.*
[b]*Species currently listed as data deficient.*

supported by a positive relationship between forest loss and fragmentation (Supporting Information).

We did not assess the number of species potentially qualifying for downlisting to lower categories of threat. Species may be listed under a particular category as a result of factors other than habitat loss. Similarly, species may have an AOO that is considerably smaller than our maximum estimate owing to highly specific habitat requirements (e.g., caves within forested areas) we could not map or owing to extirpations in some areas from overexploitation. Finally, field-based assessments of threat may be more accurate than our inferred assessments.

Results

Based on our data one amphibian species (*Dendropsophus coffees*) from Bolivia may qualify for uplisting

Table 3. Number of forest-dependent species potentially qualifying for a higher International Union for Conservation of Nature (IUCN) Red List threat category under IUCN criterion B2.[a]

	Amphibian					*Bird*					*Mammal*				
	proposed category					*proposed category*					*proposed category*				
current category	*CR*	*EN*	*VU*	*NT*	*current total*	*CR*	*EN*	*VU*	*NT*	*current total*	*CR*	*EN*	*VU*	*NT*	*current total*
CR					241					137					86
EN	1				511					293	1				192
VU		41			455		18			519		11			170
NT		17	44		285		22	62		714		2	7		98
LC	1	17	63	12	1350		33	69	33	4592		5	17	8	532
DD	2[b]	149[b]	117[b]	19[b]	698[b]			2[b]		28[b]	2[b]	39[b]	33[b]	8[b]	285[b]
Uplisted	2, 4[b]	75, 224[b]	107, 224[b]	12, 31[b]			73	131, 133[b]	33		1, 3[b]	18, 57[b]	24, 57[b]	8, 16[b]	

[a] *Abbreviations: DD, data deficient; LC, least concern; NT, near threatened; VU, vulnerable; EN, endangered; CR, critically endangered*
[b] *Species currently listed as data deficient.*

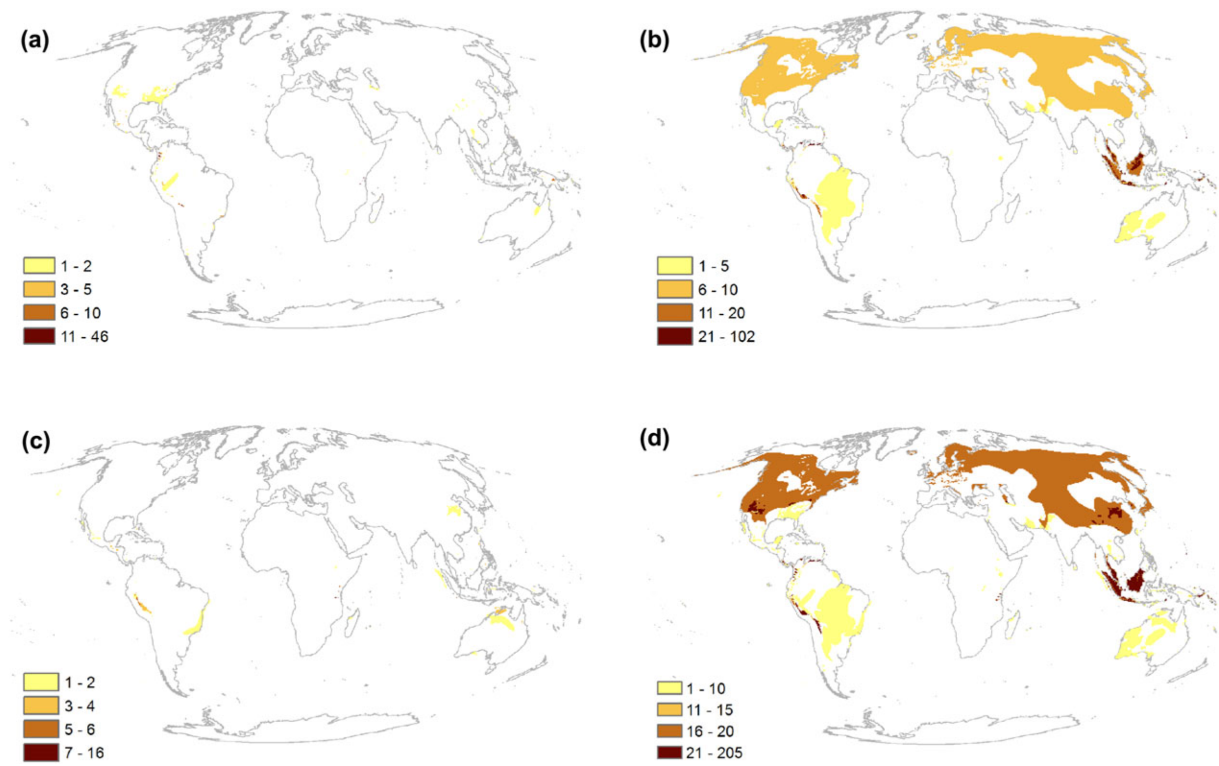

Figure 2. Number of species potentially qualifying for a higher International Union for Conservation of Nature Red List threat category: (a) amphibians, (b) birds, (c) mammals, and (d) all species combined. Data deficient species are excluded.

from least concern to vulnerable under criterion A2. *Ambystoma talpoideum* (U.S.A.) lost 24% of its forest habitat over 12 years and may qualify as vulnerable because an additional threatening factor, invasive species, exists. Forest loss and the invasive species could contribute to a rapid decline of this species that exceeds 30% over 10 years (Tables 1 and 2). We found that 196 species of amphibians had a smaller maximum AOO value than previously determined and as such may qualify for uplisting under criterion B2. This would potentially result in 12 species becoming near threatened, 107 becoming vulnerable, 75 becoming endangered, and 2 becoming critically endangered (Table 3). With inclusion of data-deficient species the number of species that qualified for uplisting may increase to 7 under criterion A2 and 483 under criterion B2 (Tables 1–3). (The distributions of many of these data-deficient species are so poorly known that our assessment of forest loss and maximum AOO may be unreliable.) Amphibian species potentially qualifying for uplisting occurred mainly in the northern Andes, Brazil's Atlantic Forest, Central America, New Guinea, Madagascar, and the Eastern Arc forests of East Africa (Fig. 2a).

Fourteen bird species potentially qualified for uplisting under criterion A2 owing to rates of forest loss alone; 1 to endangered, 3 to vulnerable, and 10 to near threatened (Tables 1 and 2). Seven species may qualify as near threatened owing to forest loss in combination with other factors driving moderately rapid declines, and *Rhinoplax vigil* (Malaysia and Indonesia) may qualify for uplisting to endangered from near threatened because of rates of forest loss in combination with intense hunting pressure. A total of 237 species potentially qualified for uplisting under criterion B2 (33 to near threatened, 131 to vulnerable, and 73 to endangered) (Table 3). *Columba trocaz* (Madeira, Portugal) was potentially near threatened owing to a combination of forest loss and hunting under A2 but potentially endangered under B2. The species affected occurred mainly in Central America, the Andes, and Southeast Asia (Fig. 2b). An additional 2 species that are currently data deficient may qualify as vulnerable under criterion B2 (Table 3).

No mammal species potentially qualified for uplisting under criterion A2, whereas 51 species potentially qualified for uplisting under criterion B2 (8 to near threatened, 24 to vulnerable, 18 to endangered, and 1 to critically endangered) (Table 3). These species were concentrated in the Andes and the islands of Southeast Asia (Fig. 2c). Inclusion of data-deficient species resulted in 2 additional species potentially qualifying as threatened under criterion A2 (1 as vulnerable and 1 as endangered) (Tables 1 and 2). For criterion B2, there were an additional 8 species that potentially qualified as near threatened, 33 as vulnerable, 39 as endangered, and 2 as critically endangered (Table 3). We identified about one-third of all species that currently qualify as globally threatened under B2 and 41% of those species that are of conservation concern. We failed, however, to detect many more species of conservation concern than currently qualify under A2 (Supporting Information).

The potential uplistings and reclassifications we identified for data-deficient species increased the percentage of threatened forest species by 37.9% for amphibians, 22.1% for birds, and 26.6% for mammals relative to the number of species in each category on the 2014 IUCN Red List. Species potentially qualifying for uplisting were concentrated in the Andes, Central America, Madagascar, the Eastern Arc forests of Africa, and the islands of Southeast Asia (Fig. 2d). Increases in the percentages of species considered at elevated conservation concern (i.e., near threatened, vulnerable, endangered, and critically endangered species were 32.8% for amphibians, 15.1% for birds, and 24.9% for mammals, including data deficient species. Details of current and potential revised red-list categories for all species are in Supporting Information.

Discussion

Forest loss from 2000 to 2012 appeared to have resulted in the extinction risk of 16 (23 including currently data-deficient species) species of amphibians, birds, and mammals increasing to a sufficient extent to uplist them to a higher extinction-risk category on the IUCN Red List (IUCN 2001). Many species' current extinction-risk category did not change despite rapid rates of forest loss (i.e., loss rates did not exceed the relevant category threshold). Amphibians accounted for 40.5% of the potential uplistings (56.5% when currently data-deficient species were included), reiterating the previously reported importance of habitat loss as a major threat to amphibians (Stuart et al. 2004). Our approach allows one to estimate forest loss and cover within forest-dependent species' distributions and thereby allows species' red-list categories to be updated rapidly when new remote sensing data become available. It demonstrates the potential benefits of using these data to assess extinction risk in the future and is a major step in the delivery of a system that can be used to assess the impact of forest loss on species. Annually updated estimates of tree cover and tree-cover loss are planned (Hansen et al. 2013); already the first 2 updates have been released (Global Forest Change 2000–2014 Data Download 2015). Knowing the distribution of threatened species and their associated threats could help target the allocation of resources to areas of particular conservation concern (e.g., hotspots where forest loss has affected large numbers of threatened species or locations where forest conservation would help achieve multiple biodiversity targets [Di Marco et al. 2016]).

We assumed that species with AOO estimates below the relevant category threshold (under criterion B2) and species that are declining would also qualify under subcriterion b2a, owing to a restricted number of locations or a severely fragmented distribution. Based on a test of randomly selected areas, we confirmed a strong relationship between forest loss and forest fragmentation (Supporting Information). These results are consistent with our experiences when conducting IUCN Red List assessments for these taxa in recent years. However, case-by-case examination of each species through ongoing efforts to reassess the status of all 3 taxonomic groups will be required.

There are known limitations associated with the Hansen et al.'s (2013) data. First, forest cover may be underestimated in dry forest habitats (Achard et al. 2014). This would not affect our results with criterion A2, but it could inflate our estimates of the number of species potentially qualifying for uplisting under criterion B2. The underestimate of forest cover was most notable in Africa (Achard et al. 2014). However, uplisted species are concentrated in humid rather than dry regions (Figure 2) (few species were from Africa). Consequently, we suggest this potential problem did not have a major effect on our results. Second, the Hansen et al. (2013) data have been criticized for mapping the cover of all trees rather than only natural forest (Tropek et al. 2014). We attempted to control for this by masking known plantations, but these data came from only a few parts of the world. Consequently, a substantial number of plantations will not have been masked. In some situations, forest may be degraded or have a structure or composition that is not suitable for all species, especially those that are highly dependent on intact primary forest and those that are highly dependent on intact primary forest. Refining our results to account for fine-scale habitat composition is not possible with current global satellite data, but these data could become available in the future. The retention of these areas as suitable habitat in our analysis could have led to an overestimation of the extent of forest in species ranges and an underestimation of forest habitat loss. Therefore, our results likely are conservative; we may have underestimated the number of species potentially qualifying for uplisting under criterion B2. We may have also underestimated the number of species potentially qualifying for uplisting under criterion A2 if natural forest is lost at a faster rate than plantation forest or natural forest is replaced by plantations. Finally, the map of Hansen et al. (2013) does not cover all areas of the planet; some areas in Oceania were omitted. Consequently, the assessment of forest loss and AOO for some species in this area may be incomplete. Expansion of the forest map to cover these areas or use of other data could fill these gaps.

The distribution maps we based our analyses on represent the best available data, but they have some limitations, in particular because they are maps of range boundaries rather than occupancy. Therefore, they are susceptible to commission errors. Removal of unsuitable areas of land cover and altitude from these range polygons reduces commission errors (Beresford et al. 2011), but some will remain. For poorly known species, particularly among amphibians and small mammals in tropical regions, they may also underestimate the actual distributional limits (Ficetola et al. 2014), although the converse may also be true in some cases. Before recategorizing species, it will be important to assess the accuracy of the distributional information. These and other factors will be considered by IUCN, and expert information and input will be solicited through processes coordinated by the relevant IUCN Red List Authority for each group (including BirdLife International for birds and Sapienza University of Rome for mammals). Species distribution maps showing probability of occurrence are becoming available based on point-locality data sets (e.g., Jetz et al. 2012). The use of these maps could result in more accurate estimates of occupancy and consequently in more accurate estimates of extinction risk. However, the accuracy of these maps remains unclear, especially for less well-known species and, in particular, due to the likely high proportion of errors in the underlying point-locality data sets.

We identified a number of ways in which our estimates could be improved. Consequently, we see this as a first step in the process of using global-scale land cover and land-cover change maps to assess species extinction risks. Species range maps are constantly being refined and updated (e.g., Joppa et al. 2015), and spatial resolution of all data sets is increasing. The relationship between loss of land cover and population decline is a complex one that is unlikely to be determined with a one-size-fit-all approach; it should be explored in more detail. The relationship between shape of the function linking land-cover change and population change may be nonlinear (convex for some species and concave for others) (Bender et al. 1998). Furthermore, the size and context of each patch will strongly affect how many individuals it can support, and the shape of the function between population and patch configuration can vary greatly (e.g., Fahrig 2001).

We did not aim to resolve these complex issues; rather, we followed the IUCN guidance on this topic: "Under criterion A, a reduction in population size may be based on a decline in area of occupancy, extent of occurrence and/or quality of habitat. The assumptions made about the relationship between habitat loss and population reduction have an important effect on the outcome of an assessment . . . .The sensible use of inference and projection is encouraged when estimating population reductions from changes in habitat . . . In all cases, an understanding of the taxon and its relationship to its habitat and the threats facing the habitat is central to making the most appropriate assumptions about habitat loss and subsequent population reduction" (IUCN Standards and Petitions Subcommittee 2014). We deliberately restricted our analysis to species that have a high degree of forest dependence and low tolerance for unforested areas and therefore assumed a linear relationship between habitat loss and population decline. Nevertheless, red-list assessors should consider explicitly the validity of this assumption on a case-by-case basis with respect to in their assessment of our results for the characteristic of each individual each species.

The IUCN Red List is the primary means of assessing species' extinction risk. However, the effort and expense involved in collecting data for red-list assessments is a burden (Rondinini et al. 2014). Rapid and cheap methods to estimate some of the relevant parameters are needed. The potential role of remote-sensing data in this respect has been highlighted (Buchanan et al. 2009; Rose et al. 2015) but not previously demonstrated at the global scale. Although the increased availability of data has enabled production of the tree cover and loss map (Hansen et al. 2013), with a spatial resolution that is ideal for mapping land cover change (Mayaux et al. 2008) and a thematic resolution that can be converted directly to forest in the IUCN Habitats Classification Scheme, it is the presentation and analysis of these data on an open-access platform that makes them particularly valuable to conservation. It enables the regular recalculation of forest loss by conservationists who no longer have to process and classify images themselves on desktops or central servers.

Our results and future annual updates based on updated data will help improve the accuracy of the IUCN Red List and provide up to date assessments for large numbers of poorly known species. This in turn contributes to improving the Red List Index (an indicator showing aggregated trends in species' extinction risk over time [Butchart et al. 2004, 2007]), which is used to track progress toward the CDB's Aichi Targets, UN Sustainable Development Goals, and the strategic objectives of a number of other international agreements (Butchart et al. 2010; Secretariat of the Convention on Biological Diversity 2014; Tittensor et al. 2014; United Nations 2014).

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Supporting Information

The relationship between forest and fragmentation change (Appendix S1), a comparison of the agreement between current red-list status of birds (2014 assessment) and status proposed from analysis of forest cover data (Appendix S2), and a summary of forest cover in 2012, forest loss from 2000 to 2012, and proposed IUCN Red List categories for all species considered (Appendix S3) are available online. The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

Literature Cited

Achard F, Eva HD, Stibig HJ, Mayaux P, Gallego J, Richards T, Malingreau JP. 2002. Determination of deforestation rates of the world's humid tropical forests. Science **297**:999–1002.

Achard F, et al. 2014. Determination of tropical deforestation rates and related carbon losses from 1990 to 2010. Global Change Biology **20**:2540–2554.

Akçakaya HR, Ferson S, Burgman MA, Keith DA, Mace GM, Todd CR. 2000. Making consistent IUCN classifications under uncertainty. Conservation Biology **14**:1001–1013.

Baillie JEM, Hilton-Taylor C, Stuart SN. 2004. IUCN red list of threatened species: a global species assessment. IUCN, Gland, Switzerland.

Bender DJ, Contreras TA, Fahrig L. 1998. Habitat loss and population decline: a meta-analysis of the patch size effect. Ecology **79**:517–533.

Beresford AE, Buchanan GM, Donald PF, Butchart SHM, Fishpool LDC, Rondinini C. 2011. Poor overlap between the distribution of Protected Areas and globally threatened birds in Africa. Animal Conservation **14**:99–107.

Bird JP, Buchanan GM, Lees AC, Clay RP, Develey PF, Yépez I, Butchart SH. 2012. Integrating spatially explicit habitat projections into extinction risk assessments: a reassessment of Amazonian avifauna incorporating projected deforestation. Diversity and Distributions **18**:273–281.

BirdLife International. 2015. IUCN red list for birds. BirdLife International, Cambridge, United Kingdom. Available from http://www.birdlife.org (accessed May 2015).

BirdLife International, NatureServe. 2014. Bird species distribution maps of the world Version 40. BirdLife International, Cambridge, United Kingdom, and NatureServe, Arlington, Virginia. Available from http://www.birdlife.org/datazone/info/spcdownload (accessed August 2014).

Buchanan GM, Butchart SHM, Dutson G, Pilgrim JD, Steininger MK, Bishop KD, Mayaux P. 2008. Using remote sensing to inform conservation status assessment: estimates of recent deforestation rates on New Britain and the impacts upon endemic birds. Biological Conservation **141**:56–66.

Buchanan GM, Nelson A, Mayaux P, Hartley A, Donald PF. 2009. Delivering a global, terrestrial biodiversity observation system through remote sensing. Conservation Biology **23**:499–502.

Buchanan GM, Donald PF, Butchart SHM. 2011. Identifying priority areas for conservation: a global assessment for forest-dependent birds. PLoS ONE **6** (e29080) DOI:10.1371/journal.pone.0029080.

Butchart SHM, et al. 2010. Global biodiversity: indicators of recent declines. Science **328**:1164–1168.

Butchart SHM, Stattersfield AJ, Bennun LA, Shutes SM, Akçakaya HR, Baillie JE, Stuart SN, Hilton-Taylor C, Mace GM. 2004. Measuring global trends in the status of biodiversity: Red List Indices for birds. PLoS Biology **2** DOI: 10.1371/journal.pbio.0020383.

Butchart SHM, et al. 2007. Improvements to the Red List Index. PLoS ONE **2** (e140) DOI: 10.1371/journal.pone.0000140.

Di Marco M, Butchart SHM, Visconti P, Buchanan GM, Ficetola GF, Rondinini C. 2016. Synergies and trade-offs in achieving global biodiversity targets. Conservation Biology **30**:189–195.

Fahrig L. 2001. How much habitat is enough? Biological Conservation **100**:65–74.

Ficetola GF, Rondinini C, Bonardi A, Katariya V, Padoa-Schioppa E, Angulo A. 2014. An evaluation of the robustness of global amphibian range maps. Journal of Biogeography **41**:211–221.

Ficetola GF, Rondinini C, Bonardi A, Baisero D, Padoa-Schioppa E. 2015. Habitat availability for amphibians and extinction threat: a global analysis. Diversity and Distributions **21**:302–311.

Global Forest Change. 2000-2014. Data download 2015. Retrieved from http://earthenginepartnersappspotcom/science-2013-global-forest/download_v12html (accessed October 2015).

Hall J, Burgess ND, Lovett J, Mbilinyi B, Gereau RE. 2009. Conservation implications of deforestation across an elevational gradient in the Eastern Arc Mountains, Tanzania. Biological Conservation **142**:2510–2521.

Hansen MC, Stehman SV, Potapov PV. 2010. Quantification of global gross forest cover loss. Proceedings of the National Academy of Sciences **107**:8650–8655.

Hansen MC, et al. 2013. High-resolution global maps of 21st-century forest cover change. Science **342**:850–853.

Hilton-Taylor C, Pollock CM, Chanson JS, Butchart SHM, Oldfield TEE, Katariya V. 2009. State of the world's species. Pages 15-41 in Vié J-C, Hilton-Taylor C, Stuart SN, editors. Wildlife in a changing world - an analysis of the 2008 IUCN Red List of Threatened Species. International Union for Conservation of Nature, Gland, Switzerland.

IUCN (International Union for Conservation of Nature). 2001. IUCN red list categories. Version 3.1. IUCN, Gland, Switzerland.

IUCN (International Union for Conservation of Nature). 2012. IUCN red list categories and criteria: version 3.1. 2nd edition. IUCN, Gland, Switzerland.

IUCN (International Union for Conservation of Nature). 2014. The IUCN red list of threatened species. IUCN, Gland, Switzerland. Available from http://wwwiucnredlistorg (accessed August 2014).

IUCN (International Union for Conservation of Nature) Standards and Petitions Subcommittee. 2014. Guidelines for using the IUCN Red List Categories and Criteria. Version 11. IUCN, Gland, Switzerland. Available from http://www.iucnredlist.org/documents/RedList Guidelines.pdf (accessed March 2016).

Jetz W, McPherson JM, Guralnick RP. 2012. Integrating biodiversity distribution knowledge: toward a global map of life. TREE **27**:151–159.

Joppa LN, et al. 2015. Impact of alternative metrics on estimates of extent of occurrence for extinction risk assessment. Conservation Biology **30**:362–370.

Mayaux P, Eva H, Brink A, Achard F, Belward A. 2008. Remote sensing of land-cover and land-use dynamics. Pages 85–108 in Chuvieco E, editor. Earth observation of global change: the role of satellite remote sensing in monitoring the global environment. Springer, New York.

Pacifici M, Santini L, Di Marco M, Baisero D, Francucci L, Marasini GG, Visconti P, Rondinini C. 2013. Generation length for mammals. Nature Conservation **5**:89–94.

Pimm SL, Russell GJ, Gittleman JL, Brooks TM. 1995. The future of biodiversity. Science **269**:347–350.

Rodrigues AS. 2011. Improving coarse species distribution data for conservation planning in biodiversity-rich, data-poor, regions: no easy shortcuts. Animal Conservation **14**:108-110.

Rodrigues AS, Pilgrim JD, Lamoreux JF, Hoffmann M, Brooks TM. 2006. The value of the IUCN Red List for conservation. Trends in Ecology & Evolution **21**:71–76.

Rondinini C, et al. 2011. Global habitat suitability models of terrestrial mammals. Philosophical Transactions of the Royal Society B **366**:2633–2641.

Rondinini C, Di Marco M, Visconti P, Butchart SHM, Biotin L. 2014. Update or outdate: long term viability of the IUCN Red List. Conservation Letters **7**:126–130.

Rose RA, et al. 2015. Ten ways remote sensing can contribute to conservation. Conservation Biology **29**:350–359.

Schad K. 2008. Amphibian population management guidelines. Amphibian Ark amphibian population management workshop. Amphibian Ark, San Diego.

Secretariat of the Convention on Biological Diversity. 2014. Global biodiversity outlook 4. Convention on Biological Diversity, Montréal.

Tittensor DP, et al. 2014. A mid-term analysis of progress toward international biodiversity targets. Science **346**:241–244.

Tropek R, Sedlacek O, Beck J, Keil P, Musilova Z, Simova I, Storch S. 2014. Comment on high-resolution global maps of 21st-century forest cover change. Science **344**:981–981.

United Nations. 2014. The millennium development goals report 2014. United Nations, New York.

World Resources Institute (WRI). 2014. WRI, Washington, D.C. Available from http://www.globalforestwatch.org/ (accessed November 2014).