LETTERS

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Carbon stock corridors to mitigate climate change and promote biodiversity in the tropics

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A key issue in global conservation is how biodiversity co-benefits can be incorporated into land use and climate change mitigation activities, particularly those being negotiated under the United Nations to reduce emissions from tropical deforestation and forest degradation[1,2]. Protected areas have been the dominant strategy for tropical forest conservation and they have increased substantially in recent decades[3]. Avoiding deforestation by preserving carbon stored in vegetation between protected areas provides an opportunity to mitigate the effects of land use and climate change on biodiversity by maintaining habitat connectivity across landscapes. Here we use a high-resolution data set of vegetation carbon stock to map corridors traversing areas of highest biomass between protected areas in the tropics. The derived corridors contain 15% of the total unprotected aboveground carbon in the tropical region. A large number of corridors have carbon densities that approach or exceed those of the protected areas they connect, suggesting these are suitable areas for achieving both habitat connectivity and climate change mitigation benefits. To further illustrate how economic and biological information can be used for corridor prioritization on a regional scale, we conducted a multicriteria analysis of corridors in the Legal Amazon, identifying corridors with high carbon, high species richness and endemism, and low economic opportunity costs. We also assessed the vulnerability of corridors to future deforestation threat.

Gross forest loss in the humid and dry tropics exceeded 90,000 $\text{km}^2\,\text{yr}^{-1}$ from 2000 to 2012 (ref. 4), driven primarily by agricultural expansion[5]. Tropical deforestation emits 0.95 Pg C yr^{-1} into the atmosphere[6] and results in widespread biodiversity loss[7]. Biodiversity in protected areas is dependent on ecological exchange with the broader landscape in which protected areas are embedded[8]. Deforestation in and around protected areas continues[9], further fragmenting tropical forest habitat and highlighting the need for additional mechanisms for forest protection[10]. At present funding levels and with increasing pressures on forests, existing conservation efforts are unlikely to prevent further loss of connectivity between protected areas and surrounding landscapes[11]. By including the United Nations programme on Reducing Emissions from Deforestation and Forest Degradation (REDD+) as a mechanism for funding land-use-based climate change mitigation in developing countries while also considering activities such as conservation and sustainable management[12], the United Nations Framework Convention on Climate Change (UNFCCC) seeks an alignment of goals and financial resources for protecting forest carbon, maintaining biodiversity and minimizing loss of ecosystem services[1,2].

Until recently, the distribution of aboveground biomass in the tropics (hereafter vegetation carbon stock (VCS), where carbon is assumed to be 50% of biomass) has been mapped at relatively coarse resolution, unsuitable for detailed spatial modelling. New data sets mapped at subkilometre resolution from space-based light detection and ranging (lidar), and high temporal frequency satellite imagery[6] allow us to characterize the spatial distribution of VCS within and between protected areas across the tropics. Our first objective was to develop a pan-tropical map of corridors that connect adjacent protected areas while passing through areas of high VCS. Our methodology employs a recent satellite-derived map of pan-tropical VCS at ∼500 m resolution[6] and the World Database on Protected Areas (WDPA). Our second objective was to illustrate how biological and economic information can be integrated to prioritize corridors according to their carbon and biodiversity co-benefits. For the Legal Amazon we conducted a multicriteria analysis to identify high-VCS corridors under threat of deforestation with high levels of biodiversity and low economic opportunity cost (EOC). We assessed threat to corridor VCS globally and for the Amazon using the human footprint database[13] and spatial projections of deforestation risk[14], respectively.

We mapped 16,257 corridors between 5,600 protected areas (Fig. 1 and Supplementary Fig. 1). Corridors covered 3.4 million km^2 and contained 51 Gt C, 15% of the total unprotected VCS of the tropical region between 23.4° north and south latitude. A mapping of corridor VCS using an alternative biomass data set for the tropics[15] yielded similar VCS amounts in corridors at the national level (Pearson correlation coefficient $(r) = 0.98$ between corridor VCS density derived from refs 6,15) and were not biased overall although estimates from ref. 15 seemed to be higher in southeast Asia (Supplementary Fig. 2). Corridor VCS differences were well correlated with countrywide differences in VCS estimates (Supplementary Fig. 3) indicating the VCS mapping methodology used to generate each biomass data set was a significant source of variation between corridor VCS estimates. VCS in corridors was similar to that in protected areas that anchor them, although scatter around the 1:1 line shows significant variability between protected areas and surrounding landscapes (Fig. 2). Fifty-nine per cent of corridors were at least as dense in VCS as their anchoring protected areas. Mean VCS in corridors in South America and Asia was lower than in protected areas in those regions (Table 1). In contrast, mean VCS in African corridors, at 130 t C ha^{-1}, was more than 1.5 times that of protected areas.

In areas of uniform biomass, corridors traversed relatively straight courses between protected areas (Fig. 1a). In areas of more fragmented biomass, corridors deflected from the shortest Euclidean path to intercept higher-VCS areas. Corridors, as with the protected areas they connect, were mapped in a variety of contexts including continuous forests (Fig. 1a), fragmented forests

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Figure 1 | Corridors passing through the densest VCS between protected areas. a–d, Central Africa (**a**), western Africa (**b**), southeast Asia (**c**) and the Guiana Shield (**d**). Corridors are shown in white, protected areas in semi-transparent grey and VCS as a gradient from low density in red to high density in green.

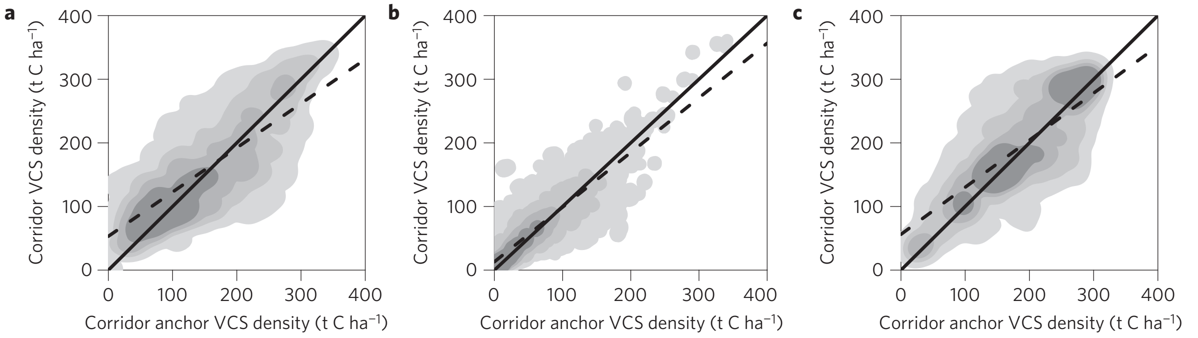

Figure 2 | Kernel density scatter plots of the relationship between VCS density of anchoring protected areas and VCS density in corridors. a, South America ($n = 4{,}563$). **b**, Africa ($n = 6{,}167$). **c**, Asia ($n = 2{,}587$). Grey scale shows the density of the data at 5, 25, 50 and 75 percentiles. Solid line, 1:1 relationship; dashed line, linear fit.

in biodiversity hotspots (Fig. 1b) and in areas with significant environmental gradients (Fig. 1c,d).

An analysis of efficiency, defined as the amount of area required to attain a given level of VCS, shows that imposing contiguity and connectivity requirements lead to less efficient VCS preservation on the national scale relative to a business as usual (BAU) approach that considers only VCS no matter where it occurs (Supplementary Fig. 4). However, high biomass areas identified in the BAU approach are more remote and under less immediate threat than corridor VCS (Supplementary Table 4 and Fig. 5). Additionality constraints render remote, low-vulnerability areas less likely to be funded under a REDD+ framework and therefore lower priority for climate mitigation efforts.

In the Legal Amazon we used the Technique for Order Preference by Similarity to Ideal Solution[16] (TOPSIS) method to score each of 721 corridors by three equally weighted criteria; VCS, mammalian biodiversity and deforestation threat. Biodiversity was quantified as either mammal species richness or endemism richness of mammals[17], resulting in two multicriteria scenarios. We calculated deforestation threat within corridors using spatially explicit deforestation projections for the Amazon from 2002 to 2030 (ref. 14). EOC, which we used to normalize corridor TOPSIS scores, was calculated as the average of the maximum of the net present value of soy, cattle and timber rents over a 30-year horizon assuming a 5% discount rate[10]. TOPSIS scores range from 0 to 1 where a value of 1 indicates a corridor with high VCS,

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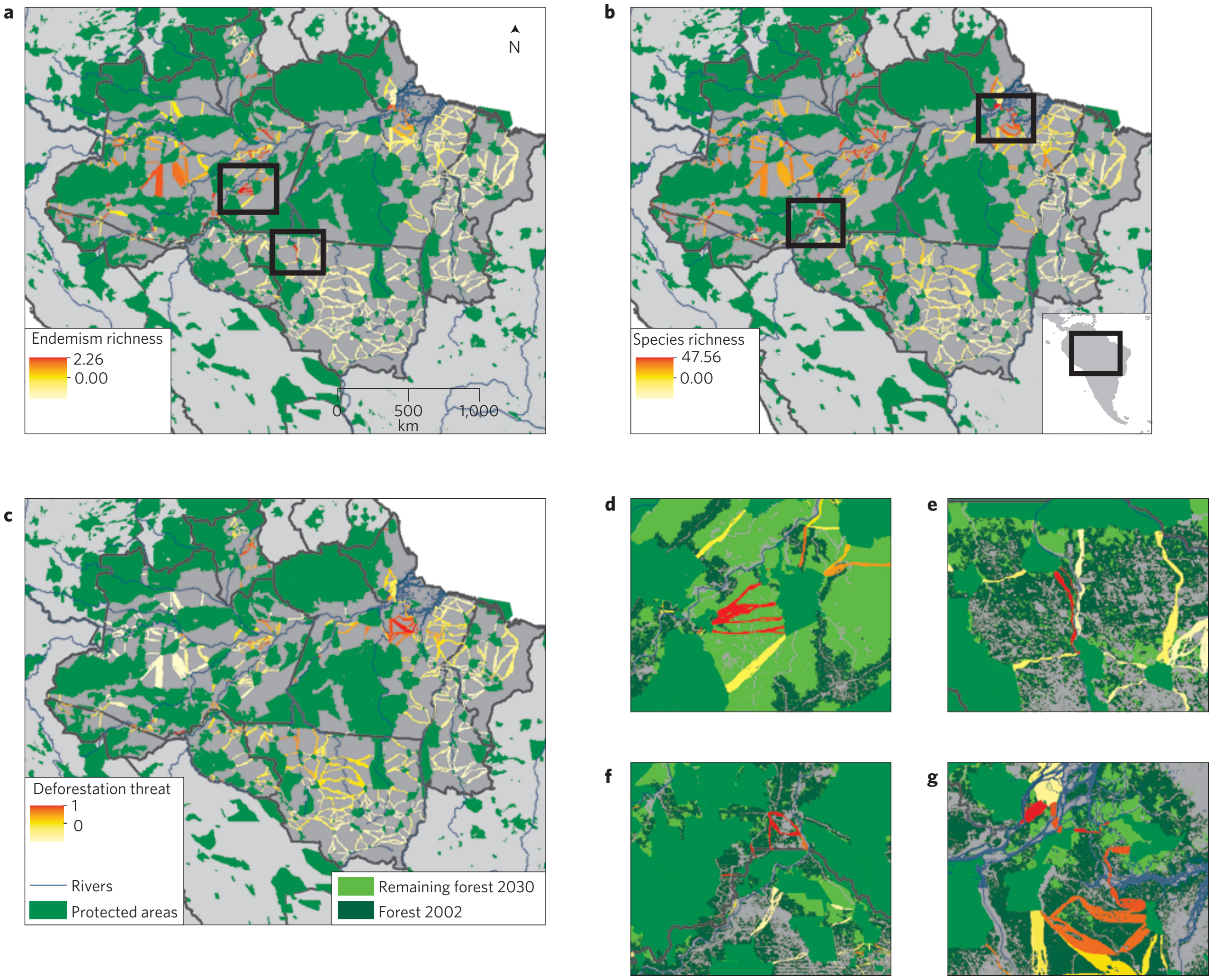

Figure 3 | Multicriteria scoring of corridors in the Brazilian Amazon across three dimensions: VCS density, mammalian biodiversity and deforestation threat. Scores were divided by EOC in units of US$10,000 ha^{-1} to yield multicriteria benefit per US$10,000. **a**,**b**, Biodiversity was measured as either endemism richness (**a**) or species richness (**b**). **c**, Deforestation threat was represented as the fraction of corridor area projected to be deforested by the year 2030 under a BAU scenario. **d**–**g**, Inset maps show areas along the Madeira River (**d**), in northern Mato Grosso (**e**), on the border of Rondônia (**f**) and in Pará at the mouth of the Amazon River (**g**). Forest cover for the year 2002 and projected remaining forest cover in 2030 (ref. 14) is depicted in inset maps **d**–**g** and symbolized by the legend in the lower right corner of **c**. Extents for insets **d** and **e** are shown left to right in **a** and extents for insets **f** and **g** are shown left to right in **b**. Corridors for all maps are symbolized using 20 quantile breaks.

high biodiversity and high deforestation threat. Average TOPSIS scores were 0.36 and 0.10 with species richness and endemism richness as a biodiversity measures, respectively. Both sets of scores were positively skewed indicating relatively few corridors traverse areas with high VCS, high biodiversity and high deforestation risk. For both biodiversity scenarios, however, scores approached 1 for some corridors, indicating presence of corridors close to the ideal solution. Dividing by EOC yielded a measure of cost for multicriteria benefits (Fig. 3).

As we mapped corridors at relatively high spatial resolution across the tropics, they can be used on scales relevant for spatial conservation planning and climate mitigation activities. An immediate application of high-VCS corridors is as a complement to existing or planned biological corridor initiatives such as those by the Amazon Conservation Association in the Amazonian headwaters[18] or the Mesoamerican Biological Corridor. Although forests are a major focus of biological corridors and of climate mitigation programmes, we did not restrict our mapping to forest ecosystems alone. Thus, the corridors can be used for planning around protected areas in lower biomass ecosystems such as cerrado or savanna, or in transitions between intact and degraded forest areas.

Table 1 | VCS density for four different VCS classifications by geographic region.

	Region-wide	Protected	Corridor	Not corridor, not protected
Africa	55.74	73.16	129.68	47.60
Asia	142.60	212.68	182.00	129.82
South America	153.96	230.00	160.12	126.59
PanTropics	101.87	168.58	151.45	83.95

Units are (t C ha^{-1}).

A BAU approach that focuses only on VCS without considering protected areas or connectivity can preserve the same amount of VCS using less area but in most cases the threats to high-VCS areas outside of corridors are lower, thus lower priority for biodiversity

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co-benefits. For example, the average human footprint[13] score for BAU areas in Brazil is close to zero because many high-VCS areas in the western Amazon are distant from major roads or navigable rivers. In other countries, such as the Democratic Republic of the Congo, threat levels in BAU areas are similar to those in corridors and in these cases protection of high-VCS forests under imminent threat may be a higher priority than preserving corridor VCS if the two do not coincide.

Carbon in corridors can be managed in a variety of ways depending on the spatial distribution of natural vegetation and on local conservation needs. Where natural vegetation is patchy, remnant high-VCS patches within corridors could be managed as stepping stones between protected areas[19]. Where vegetation between protected areas is mostly degraded, sustainable land use practices could be implemented to allow for natural regeneration of forest cover. Entire corridors can be designated as areas for sustainable livelihoods and managed as an integrated whole. Corridors that follow natural features, such as riparian corridors, or that are located in important sites in the landscape, such as headwater tributaries, could be included in payment for ecosystem service schemes. Corridor configurations are likely to have differential benefits for species owing to variability in species' tolerance to disturbance or proximity to habitat edges. Thus co-benefit management using corridors needs to incorporate local priorities.

Connectivity is only one of many considerations when identifying areas for climate mitigation. Our analysis for the Legal Amazon showed corridors can be prioritized using a multicriteria framework that considers VCS, biodiversity, deforestation threat and EOC within corridors. Several high-scoring corridors in the endemism richness scenario connect protected areas to the Juma sustainable development reserve, an early REDD project in Brazil. High endemism values in the area and projected forest loss outside the Juma reserve[20] suggest that these corridors are vulnerable to fragmentation but that they can deliver important co-benefits if protected or sustainably managed. Although many of the corridors with high scores are not at risk of conversion because they are inaccessible or in seasonally flooded areas (thus have low EOC), several high scoring corridors in the species richness scenario are on the edge of the arc of deforestation where forest fragmentation rates are high, suggesting they are good candidates for stronger protection, particularly when EOC is low.

Welfare of local communities, suitability for sustainable resource extraction, agricultural productivity and ownership are additional factors that may influence the success of climate mitigation projects, for example local ownership of forests can increase carbon storage and biodiversity relative to commercially owned forests[21,22]. Comparison with a recent analysis of protected areas[23] indicates that the WDPA is relatively complete in the Amazon (Supplementary Table 3). There are, however, extensive federal, state and private land holdings, as well as areas of unknown tenure, in between protected areas. Different ownership types require different approaches for protecting corridor VCS. For example, direct payments for ecosystem services may be feasible on private lands with clear tenure but are inappropriate for public lands or land where tenure is uncertain[24].

Protecting corridors such as those that connect the Nam Kading National Biodiversity Conservation Area in the Annamite Mountains, Laos (Fig. 1c) or the Central Suriname Nature Reserve on the Guiana Shield (Fig. 1d) can be part of a short-term strategy that aims to minimize fragmentation of existing forests as well as a longer-term strategy that maintains connectivity across gradients to allow tropical forests to reorganize in response to climate change. Although habitat loss and degradation are the primary immediate threats to tropical ecosystems[25], over longer time spans the combined effects of habitat loss, fragmentation and climate change argue for maintaining connectivity across environmental gradients to allow species to track suitable climate conditions[26]. The extent of lands eligible for REDD+ activities is potentially quite large and, with recent innovations in mapping VCS, we have new opportunities to tailor the spatial arrangement of climate mitigation activities to maintain connectivity of tropical landscapes and promote biodiversity in the face of increasingly intense land use and climate change.

Methods

We acquired protected area boundaries from the 2010 release of the WDPA (ref. 27). We selected designated protected areas for all International Union for Conservation of Nature categories to serve as anchors for corridors (Supplementary Methods).

As our goal was to map corridors traversing high VCS between protected areas, we calculated a landscape resistance surface so that high-VCS areas would be less costly to traverse and low-VCS areas would be more costly to traverse. See ref. 6 for details on creation of VCS maps. We calculated the resistance surface by taking the inverse of VCS values and recoding wide water bodies with a high-resistance value (Supplementary Methods).

For each terrestrial protected area in the WDPA we used Thiessen polygons to define the set of first-order neighbours using landscape resistance as a measure of separation between protected area boundaries[28] (Supplementary Fig. 1) and then mapped least-cost corridors between each pair of protected areas using the conditional minimum transit cost algorithm[29] (Supplementary Methods). As a sensitivity analysis, we constructed corridors using another publicly available, pan-tropical biomass data set[15].

We compared the efficiency of a corridor approach with a BAU VCS preservation approach where, within a given country, spatial location or contiguity of pixels was not considered, only biomass. To do this, we identified the minimum set of pixels that, when summed, equal the amount of VCS within corridors. We then subtracted the BAU area from corridor area and calculated the per cent difference, relative to corridor area, in the area needed to preserve the same amount of carbon as is found in corridors.

Threat of deforestation in corridors and BAU areas was estimated across the tropics using the human footprint data set[13] and for the Amazon using spatially explicit deforestation projections out to the year 2030 (ref. 14). We resampled the human footprint data to match the resolution of the VCS grids and summarized human footprint values in corridors and BAU areas. For the Amazon, we resampled deforestation projections to match the VCS grids and then calculated the fraction of each corridor projected to be deforested from 2002 to 2030.

We used the Global Administrative Areas database (http://www.gadm.org/) to summarize corridor biomass by country. We calculated mean VCS density by country and then multiplied this by the area of each country to arrive at an estimate of VCS in each country. We then repeated those steps after intersecting a binary representation of the corridor map with the VCS map and then masking out protected areas, thereby calculating unprotected VCS in corridors by country.

For the case study of the Legal Amazon, we used spatially explicit, 2-km resolution, modelled opportunity costs for soy, cattle and timber[10] to estimate costs of foregone rents associated with corridor protection. For each pixel, we calculated the maximum net present value of potential land uses assuming a high-opportunity cost scenario. The calculations are as follows:

$$\mathrm{OC} = \max(\mathrm{NPV}_{\mathrm{soy}}, \mathrm{NPV}_{\mathrm{cattle}}, \mathrm{NPV}_{\mathrm{timber}})$$

where $\mathrm{NPV}_{\mathrm{soy}}$, $\mathrm{NPV}_{\mathrm{cattle}}$ and $\mathrm{NPV}_{\mathrm{timber}}$ are net present value of returns per hectare from soybean farming, cattle ranching and timber harvesting, respectively, and OC is opportunity cost in dollars per hectare.

We used two measures of biodiversity, species richness and a weighting of species richness by range size, termed endemism richness[30]. We downloaded extent of occurrence records for all terrestrial mammals globally[31]. We gridded these geographic information system coverages at ~500 m resolution and calculated two measures of biodiversity: species richness, calculated by summing the number of ranges intersecting a given pixel; and endemism richness, calculated as follows:

$$\mathrm{ER} = \sum_{i=1}^{S} P^{-1}$$

where P is the total number of pixels in a species range, S is the number of species ranges that cover a given pixel and ER is the sum of inverse range fractions that cover a given pixel.

For the TOPSIS analysis (Supplementary Methods), we summarized species richness, endemic species richness, VCS and deforestation threat within corridors using ArcGIS zonal statistics. For each corridor we calculated fraction of corridor projected to be deforested, mean VCS and maximum values for the richness variables. We then calculated TOPSIS scores and divided them by EOC to rank corridor suitability in terms of average cost for the given criteria. We calculated

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VCS, biodiversity and deforestation threat as positive criteria to identify the most threatened corridors with high VCS and biodiversity values.

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Author contributions

S.G. and P.J. designed the study. P.J. conducted the analysis. P.J., S.G. and N.L. wrote the paper.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to S.G.

Competing financial interests

The authors declare no competing financial interests.

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