Targeted carbon conservation at national scales with high-resolution monitoring

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Terrestrial carbon conservation can provide critical environmental, social, and climate benefits. Yet, the geographically complex mosaic of threats to, and opportunities for, conserving carbon in landscapes remain largely unresolved at national scales. Using a new high-resolution carbon mapping approach applied to Perú, a megadiverse country undergoing rapid land use change, we found that at least 0.8 Pg of aboveground carbon stocks are at imminent risk of emission from land use activities. Map-based information on the natural controls over carbon density, as well as current ecosystem threats and protections, revealed three biogeographically explicit strategies that fully offset forthcoming land-use emissions. High-resolution carbon mapping affords targeted interventions to reduce greenhouse gas emissions in rapidly developing tropical nations.

carbon sequestration | forest degradation | deforestation | light detection and ranging | REDD+

Terrestrial carbon sequestration is internationally championed as a strategy for mitigating climate change. Carbon emissions from developing tropical countries are dominated by deforestation and forest degradation, which together contribute approximately 10% of the world's total emissions each year (1). This has driven an effort, known as REDD+, to reduce carbon emissions from deforestation and forest degradation, and to enhance carbon stocks through forest management (2). The geography of terrestrial carbon remains poorly known, however, leading to large uncertainties when developing estimates of carbon losses and gains over time (3). In turn, carbon stock uncertainties contribute to discounted monetary valuation, which decreases investment opportunities and thus diminishes the power of carbon-based conservation to combat climate change (4, 5). This problem has contributed to the low number and slow adoption of REDD+ programs. Consequently, carbon conservation is limited to volunteer markets or demonstration activities that are unlikely to compete financially with other land uses that generate large carbon emissions, such as oil palm plantations and surface mining (6, 7).

Transforming terrestrial carbon management into a cost-effective climate change mitigation strategy requires accurate and geographically detailed monitoring to facilitate action among multiple stakeholders, ranging from individual landowners to subnational jurisdictional agencies and national governments. The world's most common unit of land tenure, ownership, regulatory policy, and status reporting is the hectare (~2.5 acres) (8). Accurate and verifiable information on carbon stocks is needed at this high spatial resolution. Neither field plot networks nor global satellite mapping approaches have delivered spatially contiguous information on carbon stocks at a 1-ha resolution. Working at this resolution also will advance targeted conservation and management interventions designed to increase carbon stocks and protect biological diversity.

In the context of terrestrial carbon monitoring for policy and management, often insufficient emphasis is placed on the environmental conditions that determine the natural distribution of carbon stocks throughout ecosystems. Understanding the factors controlling carbon distribution is essential to targeting specific landscapes with interventions that achieve maximal returns on investments. These factors include climate, topography, geology, hydrology, and their interactions, which together set fundamental limits on the amount of carbon that may be stored on any given parcel of land. Current maps of carbon stocks based on field inventory or coarse-resolution satellite techniques do not accurately capture the natural spatial variability that ultimately underpins land use decisions at the 1-ha scale (1, 9–12).

A case study of the importance of understanding the drivers of carbon stock variation for climate change mitigation and conservation involves the megadiverse South American country of Perú. Like many rising economies, Perú is undergoing rapid land use change, driven by multisectorial interests that are altering carbon stocks throughout its ecosystems. The country harbors enormous environmental and biological gradients, ranging from the absolute desert of the Atacama on the Pacific coast to hyperpluvial forests at the base of the Andes and from arid high-elevation grasslands and large tropical ice caps to hot Amazonian lowlands, all of which strongly affect carbon storage and its interaction with human disturbances.

Perú's combination of large size, high diversity, and rapidly shifting array of human activities places the country at a crossroads between large-scale ecological loss and sustainable development. Nonetheless, despite the numerous threats to carbon storage from expanding land use throughout Perú, a portfolio of mitigation

Significance

Land use is a principal driver of carbon emissions, either directly through land change processes such as deforestation or indirectly via transportation and industries supporting natural resource use. To minimize the effects of land use on the climate system, natural ecosystems are needed to offset gross emissions through carbon sequestration. Managing this critically important service must be achieved tactically if it is to be cost-effective. We have developed a high-resolution carbon mapping approach that can identify biogeographically explicit targets for carbon storage enhancement among all landholders within a country. Applying our approach to Perú reveals carbon threats and protections, as well as major opportunities for using ecosystems to sequester carbon. Our approach is scalable to any tropical forest country.

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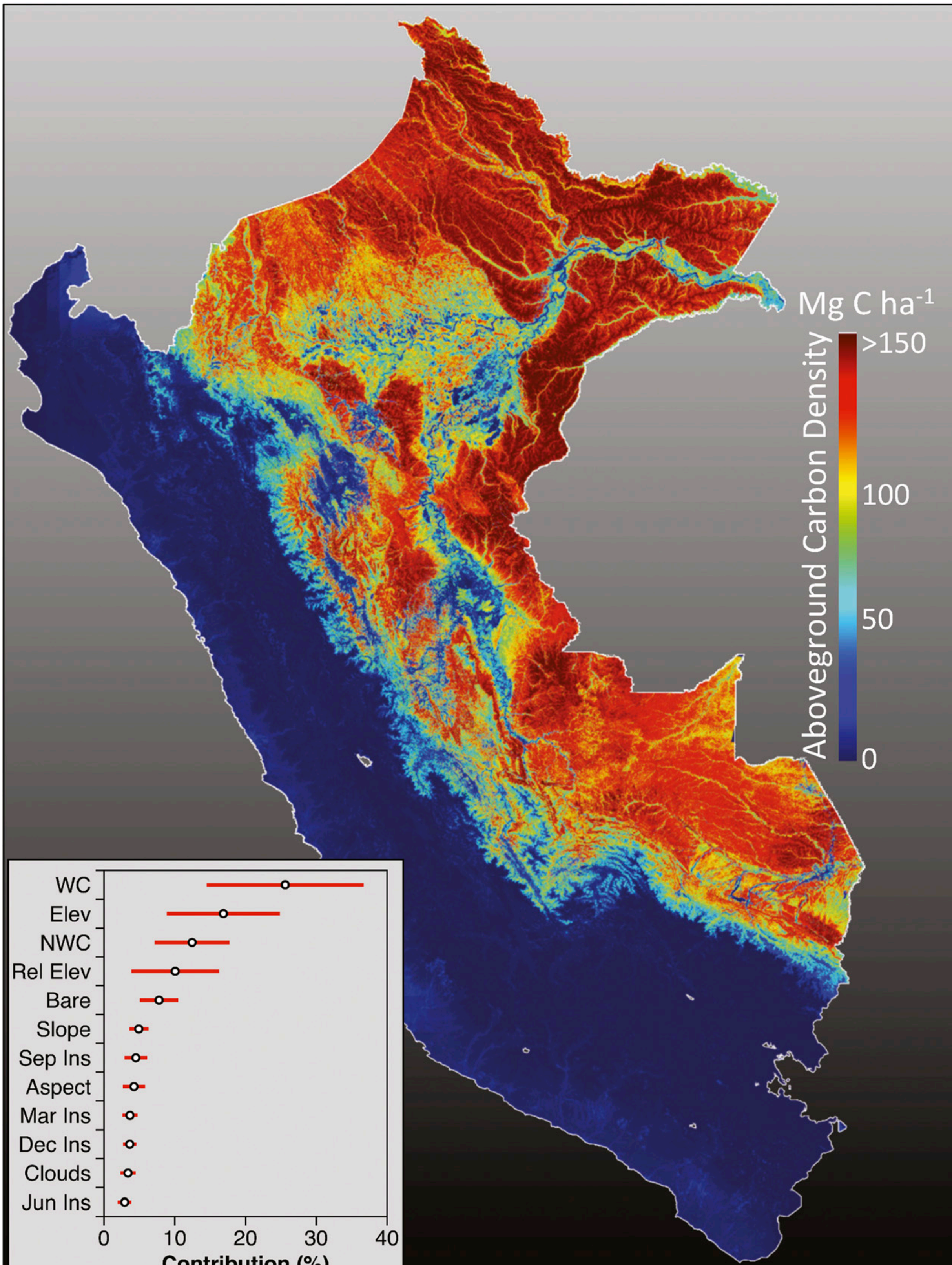

Fig. 1. The geography of aboveground carbon density (ACD) throughout Perú, derived at a 1-ha resolution with uncertainty reported for each hectare (*SI Appendix*, Fig. S9). (*Inset*) Graph reporting the relative importance of environmental factors predicting ACD (*SI Appendix*). These factors include the fractional cover of woody plants (WC), elevation, nonwoody plant cover (NWC), relative elevation above nearest water body (Rel Elev), bare substrate cover, topographic slope and aspect, solar insolation at four points of the year (e.g., Jan Ins), and cloud cover.

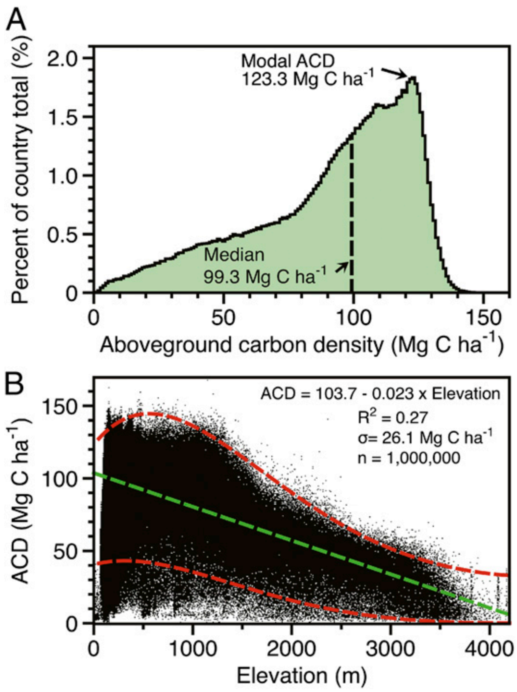

Fig. 2. (*A*) Distribution of aboveground carbon density (ACD) throughout Perú. (*B*) Decreasing ACD with increasing elevation in 1 million randomly selected hectares in intact forest. Green and red lines indicate mean and 2 SDs, respectively.

strategies can be developed to reduce or counterbalance carbon emissions from these sources; however, practical limitations require that these strategies be specific to geographic location, ecological context, and land tenure status throughout the country.

To generate a geography of carbon at the scales required for targeted conservation interventions, we integrated countrywide ecosystem sampling using airborne light detection and ranging (LiDAR) with high-resolution satellite imaging, a distributed field plot calibration and validation network, and a geospatial scaling technique to map the aboveground carbon density (ACD) of Perú at a 1-ha resolution (*SI Appendix*, Figs. S1–S7). After validating the new ACD map, we assessed natural and human controls on carbon stocks to identify opportunities for new interventions as well as limitations to potential REDD+ activities. Here we report ACD in units of Mg C ha^{-1} (Mg, metric tons) and total stock in Pg (billion metric tons).

Results and Discussion

High-Resolution Carbon Map. The high-resolution map of Perú reveals a wide range of ACD values, from <1 Mg C ha^{-1} in dry desert systems on the western, leeward side of the Andes to >150 Mg C ha^{-1} in the northeastern lowland Amazonian forests (Fig. 1). The country's total estimated aboveground carbon stock is 6.922 Pg, with a country-scale uncertainty of <1%. ACD variability in the Amazonian lowlands is driven by highly localized variations in river and stream incisions, soil fertility gradients associated with diverse geologic substrates, and hydrological conditions (*SI Appendix*). On the Pacific coast leeward of the Andes, carbon stocks are naturally suppressed by the ultra-dry climate, with localized peaks in highly managed plantations.

Field-based validation indicates high precision and accuracy of the nationally mapped ACD (*SI Appendix*, Fig. S8). Spatially explicit analyses reveal an ACD uncertainty on any given hectare of ≤20% in lowland Amazonian forests (*SI Appendix*, Fig. S9). On the dry western slopes of the Andes, uncertainty increases beyond 50% owing to the extremely sparse nature of the vegetation; however, large uncertainties in these low-carbon ecosystems result in absolute errors of only 1–4 Mg C ha^{-1}. Spatial averaging of mapped carbon stocks leads to greatly diminished overall uncertainty for a large region such as Perú (13).

Environmental Controls. Analysis of the high-resolution carbon map against satellite-derived environmental data identified the percentage cover of woody vegetation per hectare as the most important factor determining ACD throughout Perú (Fig. 1, *Inset*). Accounting for 26 ± 9% of the ACD variation, woody canopy cover is foremost a function of precipitation (14), which decreases along a steep gradient from the wet Amazon to the dry Pacific side of the Andes. In closed-canopy forests, decreases in woody canopy cover are tightly coupled to deforestation (15). Elevation also has a large overarching effect (18 ± 6%) on ACD (*SI Appendix*, Fig. S10). The next three most significant factors, including the fractional cover of nonwoody plants and bare substrate as well as relative elevation above nearest water body, accounted for an additional 32% of the ACD variation throughout the country. Within forest ecosystems, nonwoody canopy and bare substrate cover are well-known metrics of deforestation and degradation via logging and fire that removes woody plants (16–22). Relative elevation above the nearest water is highly indicative of a water deficit in deserts and grasslands or of a water surplus (which can cause anoxia) in rainforests, both of which reduce vegetation carbon storage. Together, these five factors account for approximately 75% of the variation in carbon densities throughout the country, and they integrate the effects of both natural and human-mediated processes.

To isolate the natural controls on large carbon stocks, we analyzed 1 million ha of randomly selected intact closed-canopy forest that exhibited a highly skewed ACD distribution ($\gamma = -0.831$; Fig. 2*A*). The median and modal values were 99.3 and 123.3 Mg C ha^{-1}, respectively. Departures from these values indicate conditions that mostly reduce, and in fewer cases enhance, forest carbon densities. Critically, average forest ACD decreased by 2.3 Mg C per 100 m of elevation gain (Fig. 2*B*), driven by a natural decrease in the growth-to-mortality ratio in colder montane climates (23, 24). Elevation is a key control on maximum carbon densities, yet variation at all elevations reflects additional controls, such as geology and hydrological conditions (25). These sources of variability diminish as the treeline is approached [3,720–4,260 m above sea level (ASL)], where temperature limitations are maximal.

Carbon Threats. Using a high-resolution carbon accounting approach, we quantified threats to carbon stocks by activities in current land use concessions. To date, more than 19.6 million ha of lowland Amazonian forests have been assigned to concessions for fossil fuel oil extraction and logging (Fig. 3*A*). These concessions currently hold high carbon densities, averaging 93–105 Mg C ha^{-1}, and a massive total aboveground carbon stock of 1.92 Pg (Table 1). Carbon losses from these concessions will vary based on the intensity of oil or timber extraction; however, recent studies suggest that road building and forest access generate at least a 30% decrease in carbon stock per hectare, but with high spatial variance (17, 25, 26). Applying this percentage loss to these concessions, ~0.58 Pg C is at imminent risk for emission from oil and logging in the high-carbon density Amazonian lowlands. In the submontane and montane regions of the country, oil exploration threatens an additional 0.28 Pg of carbon aboveground, or 0.08 Pg C at the 30% loss threshold. We note that ~19% of the fuel oil and logging concessions overlap geographically with protected or indigenous lands (Fig. 3), likely resulting in additional threats to the future carbon stocks of these large forest tracts.

Beyond these threats, ongoing carbon losses via deforestation for animal and crop agriculture or for urban and suburban development have resulted in low ACD levels (5 ± 5 Mg C ha^{-1}) in and around Perú's Amazonian cities (*SI Appendix*, Fig. S11). Based on Peruvian government deforestation statistics (27), roughly 1.4 million ha of forest (or 0.14 Pg C at 100 Mg C ha^{-1}) have been lost via agriculture and infrastructural development since 2000. If these rates continue, we estimate a future loss of 0.14 Pg C in the next decade (Table 1). Additional emerging threats to Perú's lowland carbon stocks include artisanal gold mining and oil palm plantations (*SI Appendix*, Fig. S12) (7, 28). Comparing current gold mining and oil palm plantation carbon stocks with intact forest carbon densities within 10 km of them, we find that these activities remove 70–95% of the aboveground carbon stock, leaving just 15–34 Mg C ha^{-1}, down from ~96 Mg C ha^{-1} (Table 1). Because the future of Peruvian gold mining and oil palm plantations is unknown, owing to the lack of land use allocation policy (e.g., concessions) and subsequent law enforcement challenges (29, 30), the threat posed by these activities to future carbon emissions cannot be better quantified.

In sum, we find that more than 2.34 Pg C in land use concessions or in the active path of infrastructural and agricultural development equates to at least 0.80 Pg of aboveground carbon at risk for emission to the atmosphere. This does not include carbon emissions associated with uncontrolled gold mining or unknown oil palm plantation development. Also not included are belowground carbon losses, which will add an additional 25–50% (31) to the total carbon threatened by land use change in Perú.

Carbon Protections. We identified current land allocations that serve to protect carbon stocks in Perú. Protected areas, such as national parks and reserves, represent one of the most robust potential sources of carbon conservation. A total of 1.82 Pg C is currently stored aboveground in 174 government-administered protected areas covering 21.7 million ha (Fig. 3, Table 1, and *SI Appendix*, Table S1). ACD averages 83.6 Mg C ha^{-1} in these protected areas, with enormous variation (SD, ±40.9 Mg C ha^{-1}) resulting from variable environmental conditions and encroaching human activity. In addition, we found that nearly 870,000 ha of government-administered Brazil nut and rubber concessions in southern Perú contain 0.11 Pg C aboveground in high-biomass forests averaging 90.6–110.3 Mg C ha^{-1}.

We analyzed carbon stocks among 1,350 nongovernment landholders whose tenure is predicated on some form of nature conservation. These include ecotourism, wildlife management and conservation concessions, and rubber, Brazil nut, and reforestation concessions (*SI Appendix*, Table S1). Individual land areas in these concessions range from 1 to 224,618 ha, and yet they store surprisingly consistent ACDs, averaging 100.9 ± 14.8 Mg C ha^{-1}. However, owing to their limited extent of just 1.7 million ha in total, these lands currently protect only 0.17 Pg C aboveground. In

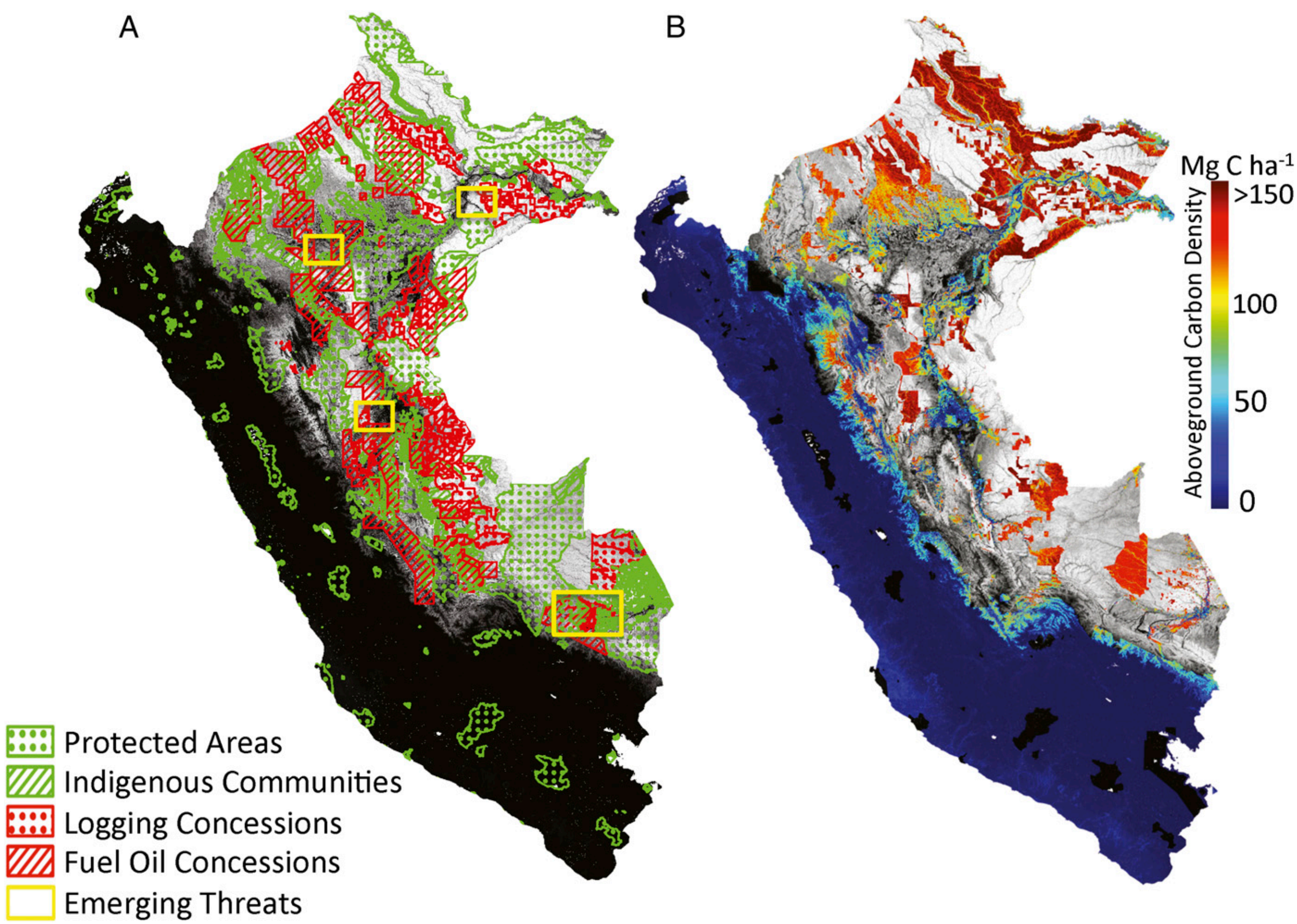

Fig. 3. The distribution of major carbon storage threats, protections, and opportunities throughout Perú. (*A*) Threats in logging and fuel oil concessions vs. current protections in government and nongovernment administered protected areas, indigenous communities, and extractive reserves. Yellow boxes highlight emerging threats of oil palm plantations and informal gold mining (*SI Appendix*, Fig. S12). (*B*) Geographic distribution and carbon densities of lands outside of known threat and protective areas.

Table 1. Carbon conservation threats, protections, and opportunities throughout Perú

Type	ACD, Mg C ha^{-1} Mean	SD	Area, ha	Total AG carbon stock, Pg
Threats				
Selective logging*	104.9	22.1	6,417,552	0.68
Oil concessions (<500 m ASL)†	93.1	32.3	13,226,773	1.24
Oil concessions (500-2,000 m)†	76.4	30.8	2,959,029	0.24
Oil concessions (>2,000 m)†	42.9	20.3	76,231	0.04
Infrastructure, animal and crop farming	5.0	5.8	1,400,000‡	0.14§
Total threats			22,679,585	2.34
Emerging threats				
Artisanal gold mining¶	34.5	29.6	37,831	0.01
Oil palm plantations#	15.4	10.9	9,684	0.001
Protections*				
Government-protected areas	83.6	40.9	21,728,378	1.82
Nongovernment-protected areas	100.9	14.8	1,743,277	0.17
Indigenous communities	93.1	27.2	9,051,407	0.84
Brazil nut concessions	110.3	16.8	869,312	0.10
Rubber concessions	90.6	19.1	16,158	0.01
Total protections			33,408,532	2.94
Opportunities				
Lowland Amazonia (<500 m ASL)	86.3	39.4	22,639,377	1.95
Sub-montane vegetation (500–2,000 m)	39.2	36.9	7,680,728	0.30
High Andean vegetation (>2,000 m)	7.4	4.8	19,353,554	0.14
Total opportunities			49,673,659	2.39

Calculations are based on land use concession and other maps shown in Fig. 3 and *SI Appendix*, Fig. S12. AG, aboveground; ASL, above sea level.
*Peruvian Ministry of the Environment (geoservidor.minam.gob.pe/geoservidor/repositorio.aspx).
†PetroPeru (www.perupetro.com.pe/wps/wcm/connect/480a8b89-0353-4879-a850-523ec62c3024/Lotes+de+Contrato+%28Mayo+2014%29.zip?MOD=AJPERES).
‡Decadal deforestation rate reported by the Peruvian Ministry of the Environment and dominated by urban-suburban development, animal ranching, and crop agriculture.
§Estimated losses over the next 10 years at the current rate of deforestation.
¶Based on Asner et al. (7); ACD mapped in active and abandoned gold mining areas.
#For a few large plantations mapped in this study (*SI Appendix*, Fig. S12); small plantations not included.

contrast, indigenous community lands contain similar ACD levels (93.1 ± 27.2 Mg C ha^{-1}) but cover ~9 million ha, thereby protecting more than 0.84 Pg C (Table 1).

The degree to which indigenous lands should be considered as protective of carbon stocks remains unclear, given the plethora of land use and land encroachment issues and the deficiency of knowledge regarding native land uses (30). Nonetheless, evidence gathered from Brazil's indigenous territories strongly suggests that these lands are far more carbon-protective compared with neighboring forms of land use (32). Combining all current forms of protective land uses, we estimate that a total of 2.94 Pg C are currently stored aboveground on 33.4 million ha throughout Perú.

Carbon Opportunities. Spatially explicit tracking of current carbon threats and protections reveals new opportunities for carbon conservation, which vary widely based on underlying environmental conditions that naturally limit or promote carbon storage. First, there is a major opportunity to avoid carbon emissions by establishing additional forest protections in biogeographically distinct regions of Perú (Fig. 3*B*). Much of the opportunity rests in the lowland Amazonian region of Loreto, where very high carbon densities were found. Additional major lowland targets exist in the central and southern lowlands of Ucayali and Madre de Dios. A total of 1.95 Pg C are available aboveground in the Amazonian lowlands for use in emission avoidance (Table 1). In addition, a large amount of fragmented land near lowland urban and rural centers already contains highly degraded carbon densities. Comparing degraded areas with neighboring lowland forests with high ACD levels of 86.3 ± 39.4 Mg C ha^{-1}, we contend that lowland degraded areas offer large carbon gains if assigned to restoration projects.

A second opportunity exists in the submontane region between lowland Amazonia and the Andean highlands (500-2,000 m ASL), where we mapped 0.30 Pg C available for protection (Fig. 3*B* and Table 1). These lands contain a highly variable average ACD of 39.2 ± 36.7 Mg C ha^{-1} on 7.7 million ha, with carbon densities decreasing with increasing elevation. Once in the high Andes above 2,000 m ASL, potential carbon conservation gains diminish as ACD levels drop to 7.4 ± 4.8 Mg C ha^{-1}. Together, submontane and montane lands offer 0.44 Pg C aboveground and perhaps 50% more belowground for new protection.

Beyond the establishment of these new carbon protections, the current portfolio of government-protected areas spans a wide range of enforcement levels, with some areas strictly guarded against land use and others unmanaged or unenforced altogether (33) (*SI Appendix*, Table S1). Government-protected areas represent just 26% of the total aboveground carbon stock of Perú, and more than 85% of the aboveground carbon stored in these protected areas is found in just 10 parks and reserves, of which only 4 are afforded the status of full protection. As a result, the majority of Perú's government-protected areas remain accessible to land use. Transitioning partially protected areas to full protection would ensure that carbon is conserved to help counterbalance at least 0.8 Pg of aboveground carbon at risk for emission from land use concessions. Moreover, our analyses reveal that an average of 95.1 Mg C is sequestered in aboveground vegetation for every hectare of Amazonian forest placed under full protection, with up to 50% more invested belowground (*SI Appendix*, Fig. S13).

Targeted Carbon Conservation. The key to using ecosystems to help achieve national emissions reduction goals rests in devising interventions that target sufficient areas of biogeographically appropriate land. High-resolution mapping reveals the key abiotic factors, including elevation and climate, that generate a natural carbon template on which policies and management can work to maximize carbon storage. Our analysis reveals that 2.94 Pg of aboveground carbon is currently stored on land allocated for protective activities throughout Perú, compared with more than 2.34 Pg threatened by land use change. Carbon densities are distributed similarly throughout the country in protected and threatened areas (Fig. 4*A*), and these two areas show nearly the same carbon storage response to increasing elevation (Fig. 4*B*). By integrating this information spatially, we identified opportunities to secure an additional 2.39 Pg of aboveground carbon.

To secure additional aboveground carbon on such a large scale, it is critically important to decrease forest disturbance in land use concessions. Our forecast of 0.8 Pg of aboveground carbon emissions is driven largely by oil and timber extraction plans, but emissions can be reduced by restricting road access to oil concession areas and via reduced-impact logging (34, 35). Studies show that reduced-impact logging greatly reduces collateral canopy damage and leaves more forest cover (34, 36, 37), which is a principal determinant of carbon stocks throughout Perú (Fig. 1). The concept of reduced-impact oil exploration remains largely untested (38), suggesting the need for close monitoring of these concessions. The cobenefits of reduced disturbance include more secure hydrological functioning and biodiversity.

Any practical effort to achieve a net neutral carbon balance depends not only on reducing gross emissions, but also on promoting carbon uptake at a gross rate that balances losses. For example, field studies suggest that western Amazonian forests sequester an average of 0.45 Mg C ha^{-1} y^{-1} aboveground (39). Thus, to offset our estimated 0.8 Pg of aboveground carbon in imminent danger of release via land use, ∼18 million hectares of additional forest protection will be required for active carbon sequestration over the next 100 y. Currently, the unprotected forests of the lowland Amazon and submontane Andes are the most viable candidates for this additional forest protection, offering ∼30 million ha of new protection (Table 1). Moreover, a geographically distributed portfolio of new areas across widely varying environmental conditions will be needed to increase resilience to losses incurred from unplanned land use encroachment and climate change (40). Drought poses a particular threat to carbon stocks (39, 41), and, given the regional specificity of past mega-droughts (42), maintaining a diverse national portfolio of forest carbon protections will be critically important in the coming decades.

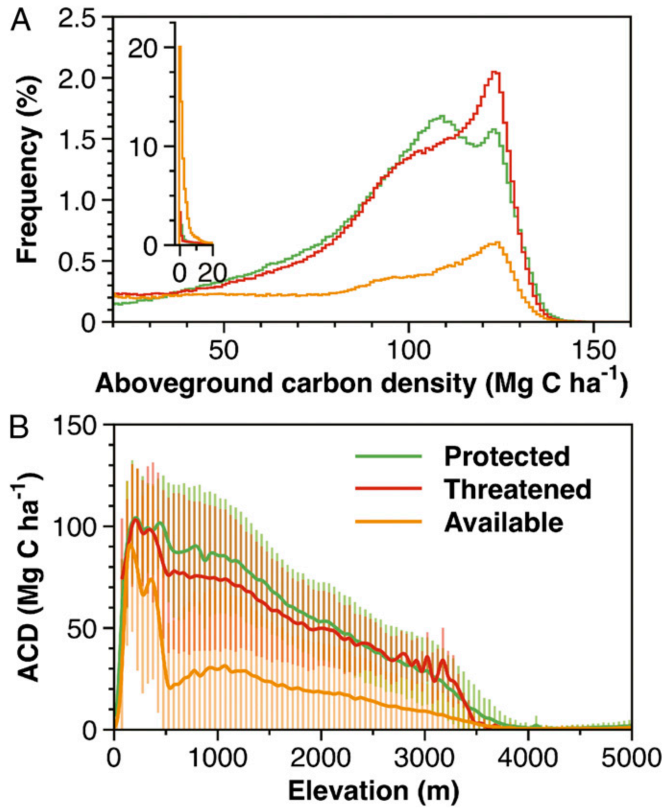

Fig. 4. (*A*) Percentage distribution of threatened, protected, and available aboveground carbon density throughout Perú. (*B*) Changes in aboveground carbon density (ACD) with elevation change in threatened, protected, and available categories. Vertical bars indicate 2 SDs.

Tactical Carbon Management at Scale. Land use can be traced to most human sources of greenhouse gases. Emissions occur directly through land change processes, such as deforestation, or indirectly via transportation networks and industries supporting natural resource extraction, energy and food production, and other essential societal needs (43). To minimize the effects of emissions on the climate, natural ecosystems are needed to store as much carbon as possible and to offset gross emissions through sequestration, even in the face of a changing climate system. Managing this critically important resource must be achieved tactically if it is to be cost-effective. This will allow for successful regulatory, market-based, and volunteer actions at multiple geographic scales, using specific land parcels distributed among currently threatened, protected, and still-unallocated ecosystems.

Here we have shown that high-resolution carbon mapping can uniquely identify biogeographically explicit targets for carbon storage enhancement at a national scale. Field-based inventory plot networks are not designed to deliver this type of spatially explicit information, hectare by hectare, at scales ranging from local to subnational to national levels; however, doing so will promote the involvement and participation of stakeholders whose efforts range in scale from small landholdings (1 ha) to large government-administered regions of millions of hectares. The approach that we have developed and implemented can be rapidly updated at low cost, significantly reducing the lag times of years to decades incurred when using field plot inventory approaches alone. Our project cost was approximately 1 US cent ($0.01) per hectare when applied over the entire country of Perú. The common misunderstanding that airborne LiDAR is overly expensive is an artifact of the past use of airborne LiDARs over too small of a geographic extent and without quantitative methods for scaling the LiDAR data up to full geographic coverages at regional to national levels. The integrated use of massive airborne LiDAR sampling and wall-to-wall high-resolution satellite information overcomes the cost-to-coverage barrier. As a result, this high-resolution, rapid assessment methodology can be replicated and applied anywhere in the world (44).

Despite the demonstrable gains in geographic coverage, reduced cost, and increased accuracy of carbon mapping presented here, we recognize the importance of additional considerations when developing tactical carbon conservation approaches at the national level. These include the marginal cost of land, biodiversity value, ownership issues (including indigenous rights), and other factors. Nonetheless, we contend that high-resolution mapping, with known accuracies at a 1-ha resolution, provides a tangible medium with which stakeholders can engage one another. In effect, the map facilitates a dialogue based on something real: the amount of carbon stored on each hectare of land under the ownership, control, and/or interest of all potential parties.

Finally our map-based analysis serves as only one (albeit major) input into a larger set of calculations of baseline carbon stocks and emissions in the context of international and subnational REDD+ investments. In the case of Perú, a business-as-usual emissions baseline is needed, and our carbon map and the historical analysis component of our study can be readily used to develop a high-resolution, geographically explicit emissions baseline. This already has been done retrospectively, on an annual basis dating back to 1999, at a subnational scale for the Madre de Dios region (25). Expanding this to the national level is straightforward using deforestation data already generated by the Peruvian Ministry of the Environment (27). More work is needed to bring these component inputs together in an operational framework, however. All nations will need to implement such an approach to manage their contributions to climate change.

Methods

The study covers the 128.5 million-ha country of Perú. The vast majority of the aboveground carbon is found in humid forests stretching from the Andean treeline to the lowland Amazonian forests as far as the Ecuadorian, Colombian, Brazilian, and Bolivian borders. A much smaller amount of dry tropical forest exists primarily in the northern portion of the country, and those areas were fully incorporated into the study. The study also included less well-understood regions, including alpine tundra and high-altitude grasslands, as well as woodlands and shrublands in the inter-Andean corridor.

Our mapping approach is based on the original high-resolution method presented by Asner (45), with a series of improvements developed through testing and analysis in a wide variety of countries and ecosystems (25, 46–49). The approach combines readily available satellite and geographic information system datasets at 1-ha or finer resolution with airborne LiDAR and field plot calibration data in a modeling framework to develop maps of ACD with spatially explicit uncertainty estimates (*SI Appendix*).

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