Forest carbon prospecting for climate mitigation

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Abstract

Carbon finance projects that protect tropical forests could support both nature conservation and climate mitigation goals. Global demand for nature-based carbon credits is outpacing their supply, due partly to gaps in knowledge needed to inform and prioritize investment decisions. Here, we show that at current carbon market prices the protection of tropical forests can generate investible carbon amounting to 2.4 (±1.1) GtCO2e yr-1 globally. We further show that financially viable carbon projects could generate return-on-investment amounting to $77.5b y-1 in net present value (Asia-Pacific: $38.4b y-1; Americas: $33.4b y-1; Africa: $5.7b y-1). However, we also find that ~75% (1.24 billion ha) of forest carbon sites would be financially unviable for failing to break even over the project lifetime. From a conservation perspective, unless carbon prices increase in the future, it is imperative to implement other conservation interventions, in addition to carbon finance, to safeguard carbon stocks and biodiversity in vulnerable forests.

Full Text

The COVID-19 pandemic may give rise to a cleaner and greener global future that emphasizes sustainable development, a circular economy and investments in nature-based solutions[1]. Indeed, our ability to achieve green growth on our path to economic recovery may be critical for addressing an even greater and more insidious existential crisis, which is that of climate change.

Globally, natural climate solutions may provide up to one-third of the cost-effective mitigation needed to achieve the <2°C target of the Paris Climate Agreement[2] . These solutions include the conservation, restoration and improved management of forests, wetlands, grasslands, and agricultural lands to increase carbon dioxide sequestration, reduce emissions and enhance climate resilience[2,3]. Protecting and ensuring the health of natural ecosystems are also important for conserving biodiversity, providing clean air and water, safeguarding food security and sustaining livelihoods[2,4].

The climate mitigation potential and co-benefits of natural climate solutions present exciting new opportunities for the public and private sectors to meet their climate goals, invest in carbon finance, and contribute to addressing the impacts of climate change[5,6]. Indeed, the transacted volume of nature-based carbon credits in the voluntary carbon market grew by over 250% between 2016 and 2018, from 14 $MtCO_2e$ to 51 $MtCO_2e$[6].

The growing demand for nature-based carbon credits is outpacing their supply. The bottleneck in shovel-ready carbon projects may be due in part to gaps in knowledge critical for supporting and informing investment decisions. For example, while the protection of tropical forests could in principle contribute substantially to climate mitigation by safeguarding their forest carbon[7], these carbon stocks may not all be fundable through carbon finance, and hence not all be investible.

In fact, only the subset of forest carbon stocks that are under imminent threat of decline or loss if left unprotected by a conservation intervention may be certifiable[8,9]. This criterion of ‘additionality’ is a precondition for certifying all carbon credits, including nature-based credits traded in the voluntary carbon market, under the rules of the United Nations Framework Convention on Climate Change[8].

We modeled the magnitude of certifiable carbon from forest carbon projects and its climate mitigation potential to produce a global investible forest carbon map (Fig. 1).

This analysis presents spatially explicit information on the relative climate mitigation potential of protecting tropical forests, accounting for not only the carbon stock of a forest, but also the risk of losing that forest[8,10] (Fig. 1; see Methods).

Our analysis shows that the protection of tropical forests worldwide could generate investible carbon amounting to 2.4 (±1.1) GtCO2e yr^{-1} (Fig. 1; Table 1). Much of this carbon would originate from the Americas (1098.0 ± 515.7 $MtCO_2e\ yr^{-1}$) and the Asia-Pacific region (789.0 ± 330.8 $MtCO_2e\ yr^{-1}$). The African continent has substantially lower potential for generating investible carbon from tropical forest projects (533.2 ± 318.7 $MtCO_2e\ yr^{-1}$).

Our estimates of investible carbon are 33–43% lower than those reported in previous studies[2,3], which were largely based on aggregated country level data on carbon stocks and deforestation rates. Furthermore, our analysis also incorporates several criteria of the Voluntary Carbon Standard (VCS), such as the requirement to set aside buffer credits[8], not considered in other studies[2,3]. As such, we are able to compare our estimates of investible carbon with empirical data on verified carbon units reported from 28 real world VCS projects (verra.org/), and report a relatively strong correlation between the two datasets (R=0.53, p<0.05, Root Mean Square Error=0.53; Fig. S1; see Methods).

Table 1. Global, regional, and country level estimates of investible carbon and return-on-investment (based on net present value).

Region	Country	Investible carbon ($tCO_2e\ yr^{-1}$)	Net present value (USD y^{-1})
Global (Pantropic)		**2,420,169,000 (±1,165,139,000)**	**77,540,431,000 (±25,606,498,000)**
Americas		**1,098,009,000 (±515,691,000)**	**33,414,594,000 (±12,152,680,000)**
	Argentina	7,648,000 (±4,427,000)	308,061,000 (±126,780,000)
	Antigua and Barbuda	32,000 (±22,000)	1,072,000 (±614,000)
	Bonaire, Sint Eustatius and Saba	2,000 (±1,000)	17,000 (±7,000)
	Bahamas	320,000 (±165,000)	14,235,000 (±4,966,000)
	Belize	3,300,000 (±1,892,000)	101,234,000 (±38,320,000)
	Bolivia, Plurinational State of	130,305,000 (±61,355,000)	4,537,869,000 (±1,341,622,000)
	Brazil	578,524,000 (±255,050,000)	18,864,696,000 (±6,610,495,000)
	Barbados	0 (±0)	9,000 (±4,000)
	Chile	0 (±0)	0 (±0)
	Colombia	54,440,000 (±26,086,000)	1,200,642,000 (±497,545,000)
	Costa Rica	2,054,000 (±1,273,000)	18,084,000 (±6,581,000)
	Cuba	7,859,000 (±4,741,000)	196,755,000 (±65,477,000)
	Curaao	5,000 (±3,000)	54,000 (±7,000)
	Cayman Islands	33,000 (±19,000)	634,000 (±89,000)
	Dominica	0 (±0)	0 (±0)
	Dominican Republic	3,027,000 (±1,791,000)	100,782,000 (±42,249,000)
	Ecuador	17,422,000 (±8,539,000)	525,551,000 (±204,200,000)
	Guadeloupe	61,000 (±39,000)	1,264,000 (±508,000)
	Grenada	12,000 (±7,000)	64,000 (±8,000)
	Guatemala	7,411,000 (±4,265,000)	207,218,000 (±68,050,000)
	French Guiana	5,975,000 (±1,840,000)	37,584,000 (±6,334,000)
	Guyana	24,488,000 (±8,588,000)	332,155,000 (±76,627,000)

	Honduras	5,109,000 (±3,099,000)	99,320,000 (±38,976,000)
	Haiti	365,000 (±216,000)	9,016,000 (±3,222,000)
	Jamaica	622,000 (±347,000)	15,077,000 (±4,585,000)
	Saint Kitts and Nevis	9,000 (±6,000)	141,000 (±95,000)
	Saint Lucia	29,000 (±17,000)	594,000 (±162,000)
	Mexico	69,766,000 (±48,247,000)	2,257,596,000 (±1,395,082,000)
	Montserrat	4,000 (±3,000)	52,000 (±33,000)
	Martinique	18,000 (±12,000)	351,000 (±193,000)
	Nicaragua	5,919,000 (±3,818,000)	109,885,000 (±52,511,000)
	Panama	3,950,000 (±2,232,000)	57,901,000 (±14,633,000)
	Peru	68,857,000 (±25,910,000)	1,338,466,000 (±196,156,000)
	Puerto Rico	47,000 (±28,000)	1,692,000 (±731,000)
	Paraguay	34,064,000 (±21,378,000)	1,441,391,000 (±711,074,000)
	El Salvador	980,000 (±663,000)	25,265,000 (±14,035,000)
	Suriname	16,530,000 (±6,305,000)	223,935,000 (±67,681,000)
	Turks and Caicos Islands	32,000 (±17,000)	1,162,000 (±335,000)
	Trinidad and Tobago	406,000 (±239,000)	9,626,000 (±3,136,000)
	Saint Vincent and the Grenadines	5,000 (±3,000)	15,000 (±3,000)
	Venezuela, Bolivarian Republic of	48,373,000 (±23,045,000)	1,375,029,000 (±559,519,000)
	Virgin Islands, British	1,000 (±0)	19,000 (±4,000)
	Virgin Islands, U.S.	2,000 (±1,000)	83,000 (±31,000)
Africa		**533,210,000 (±318,678,000)**	**5,700,130,000 (±1,508,084,000)**
	Angola	69,419,000 (±44,298,000)	873,398,000 (±239,173,000)
	Burundi	183,000 (±159,000)	918,000 (±1,055,000)
	Benin	2,014,000 (±1,811,000)	16,598,000 (±15,248,000)
	Burkina Faso	304,000 (±298,000)	642,000 (±1,174,000)

Botswana	484,000 (±465,000)	3,928,000 (±4,870,000)
Central African Republic	38,320,000 (±25,241,000)	134,132,000 (±10,382,000)
Côte d'Ivoire	69,419,000 (±44,298,000)	873,398,000 (±239,173,000)
Cameroon	27,841,000 (±12,154,000)	468,304,000 (±73,405,000)
DR Congo	115,691,000 (±48,676,000)	829,881,000 (±62,382,000)
Congo	30,412,000 (±11,592,000)	449,714,000 (±48,969,000)
Comoros	8,000 (±5,000)	18,000 (±0)
Djibouti	0 (±0)	0 (±0)
Eritrea	0 (±0)	0 (±0)
Ethiopia	13,996,000 (±10,672,000)	158,458,000 (±66,874,000)
Gabon	25,706,000 (±7,887,000)	358,117,000 (±47,273,000)
Ghana	5,347,000 (±4,178,000)	57,627,000 (±20,244,000)
Guinea	6,070,000 (±5,020,000)	55,691,000 (±25,736,000)
Gambia	116,000 (±109,000)	2,255,000 (±2,580,000)
Guinea-Bissau	1,225,000 (±1,007,000)	13,313,000 (±7,477,000)
Equatorial Guinea	2,282,000 (±671,000)	58,857,000 (±7,488,000)
Kenya	3,205,000 (±2,253,000)	53,284,000 (±22,251,000)
Liberia	4,661,000 (±1,304,000)	127,526,000 (±12,587,000)
Madagascar	8,630,000 (±6,428,000)	77,596,000 (±30,107,000)
Mali	1,305,000 (±1,211,000)	7,397,000 (±10,068,000)
Mozambique	37,632,000 (±27,570,000)	475,324,000 (±165,761,000)
Mauritania	0 (±0)	0 (±0)
Malawi	2,111,000 (±1,521,000)	23,087,000 (±8,883,000)
Mayotte	8,000 (±4,000)	53,000 (±6,000)
Namibia	289,000 (±278,000)	262,000 (±310,000)
Niger	0 (±0)	0 (±0)
Nigeria	11,270,000 (±8,431,000)	123,691,000 (±49,010,000)
Rwanda	71,000 (±58,000)	623,000 (±685,000)
Sudan	1,236,000 (±1,223,000)	749,000 (±2,151,000)

Senegal	2,634,000 (±2,400,000)	16,832,000 (±17,041,000)
Sierra Leone	901,000 (±479,000)	17,800,000 (±1,879,000)
Somalia	273,000 (±249,000)	226,000 (±26,000)
South Sudan	15,719,000 (±14,012,000)	22,681,000 (±26,038,000)
Sao Tome and Principe	49,000 (±22,000)	1,323,000 (±338,000)
Chad	2,324,000 (±2,040,000)	21,501,000 (±14,532,000)
Togo	1,109,000 (±1,018,000)	3,271,000 (±3,679,000)
Tanzania, United Republic of	45,807,000 (±33,473,000)	667,900,000 (±285,635,000)
Uganda	2,325,000 (±1,840,000)	7,888,000 (±1,431,000)
South Africa	344,000 (±246,000)	3,287,000 (±1,017,000)
Zambia	40,476,000 (±28,510,000)	503,656,000 (±179,552,000)
Zimbabwe	5,650,000 (±5,338,000)	13,153,000 (±18,217,000)
Asia-Pacific	**788,950,000 (±330,770,000)**	**38,425,706,000 (±11,945,734,000)**
Bangladesh	5,640,000 (±3,017,000)	316,162,000 (±144,884,000)
Brunei Darussalam	1,491,000 (±644,000)	68,868,000 (±22,812,000)
China	38,407,000 (±16,379,000)	2,039,668,000 (±643,915,000)
Indonesia	312,145,000 (±124,176,000)	15,437,841,000 (±4,787,115,000)
India	67,688,000 (±35,388,000)	2,983,599,000 (±1,115,359,000)
Cambodia	38,444,000 (±16,975,000)	2,225,685,000 (±785,231,000)
Lao People's Democratic Republic	30,022,000 (±11,939,000)	1,463,878,000 (±399,438,000)
Sri Lanka	5,650,000 (±2,963,000)	299,090,000 (±128,053,000)
Myanmar	47,762,000 (±20,663,000)	2,056,144,000 (±563,612,000)
Malaysia	72,657,000 (±25,893,000)	3,942,487,000 (±1,012,462,000)
Philippines	13,750,000 (±5,772,000)	575,079,000 (±158,503,000)
Singapore	0 (±0)	0 (±0)

Thailand	2,000 (±1,000)	92,000 (±44,000)
Timor-Leste	53,025,000 (±22,738,000)	2,724,504,000 (±850,265,000)
Taiwan	640,000 (±294,000)	30,380,000 (±10,023,000)
Viet Nam	812,000 (±346,000)	29,316,000 (±7,407,000)
Australia	32,619,000 (±13,519,000)	1,713,860,000 (±518,748,000)
Papua New Guinea	0 (±0)	0 (±0)

Globally, the top five countries in terms of investible carbon are Brazil (578.5 ± 255.1 $MtCO_2e\ yr^{-1}$), Indonesia (312.1 ± 124.2 $MtCO_2e\ yr^{-1}$), Bolivia (130.3 ± 61.4 $MtCO_2e\ yr^{-1}$), Democratic Republic of Congo (115.7 ± 48.7 $MtCO_2e\ yr^{-1}$) and Malaysia (72.7 ± 25.9 $MtCO_2e\ yr^{-1}$) (Fig. 1; Table 1).

Perhaps unsurprisingly, much of this investible carbon potential remains unrealized. For example, the total volume of verified carbon units produced in these top five countries from existing VCS projects represents <0.1% (0.98 $MtCO_2e\ yr^{-1}$) of the countries' total investible carbon potential estimated from our analysis (1.2 $GtCO_2e\ yr^{-1}$) (Tables 1, S1)[11,12].

Barriers to the establishment of forest carbon projects may include competing interests and priorities from other economic sectors (e.g. agriculture), lack of enabling conditions and policies, governance and institutional constraints, and prohibitively high technical entry bar[11-13]. Many of these barriers may be overcome if actionable information regarding both the financial risks and return-on-investment of projects is available to incentivize solutions.

Indeed, investible carbon projects may not all be profitable. The financial viability of a project depends on a range of factors, including operational costs and carbon pricing, as well as political risk, which may vary with location and over time[14].

We modeled the relative profitability of these projects to produce a global forest carbon return-on-investment map (Fig. 2).

We based our analysis on several simplifying assumptions (see Methods for details). Briefly, we applied a cost estimate of \$25 ha^{-1} for project establishment, and \$10 $ha^{-1}\ y^{-1}$ for subsequent years for project maintenance. We also assumed a constant carbon price of \$5.8 t^{-1}CO2e for the first five years, followed by a 5% price appreciation for the subsequent years over a project timeframe of 30 years[14]. Finally, we applied a risk-adjusted discount rate of 10% in our calculation of net present values (NPV) for the return-on-investment of tropical forest carbon projects.

We find that the vast majority of financially viable (i.e. yielding positive NPV) and most profitable forest carbon sites (>$461 ha^{-1} y^{-1}; 90th percentile) are located in the Asia-Pacific region with NPV amounting to $38.4b y^{-1}, compared to the Americas ($33.4b y^{-1}) and Africa ($5.7b y^{-1}) (Figs. 2 & S2; Table 1). This largely reflects a combination of high deforestation rates and high carbon density of the tropical forests in Asia[15].

The top five countries with highest return-on-investment are Brazil ($18.9b y^{-1}), Indonesia ($15.4b y^{-1}), Bolivia ($4.5b y^{-1}), Malaysia ($3.9b y^{-1}) and India ($3.0b y^{-1}) (Figs. 2 & S2; Table 1).

Globally, ~75% (1.24 billion ha) of the investible forest carbon sites would be financially unviable for carbon finance for failing to break even over the project lifetime (i.e. yielding negative NPV; Fig. 2). Importantly, these forests represent forgone climate mitigation at a rate of 0.7 $GtCO_2e$ yr^{-1}. From a forest conservation perspective, these findings suggest that carbon finance will fail to protect the vast majority of investible carbon sites, which are also, by definition, vulnerable to deforestation (Figs. 2 & S2; Table 1).

However, if global demands for nature-based carbon credits continue to grow[6], future carbon prices may also increase. We modeled the effects of carbon pricing on the financial viability of forest carbon sites globally. We find that carbon pricing at $15 t$^{-1}CO_2e$ and $50 t$^{-1}CO_2e$ are needed to protect 50% and 80% of investible carbon sites, respectively (Fig. 3). Further carbon price increases above $25 t$^{-1}CO_2e$ would only bring marginal forest conservation and climate mitigation benefits (Fig. 3).

Nevertheless, it is important to note that some financially viable but less profitable forest carbon sites will struggle to compete with lucrative land uses, particularly in countries such as Brazil and Indonesia, which are the world's major producers of soy and palm oil, respectively[14]. In other countries, such as the Democratic Republic of the Congo, hydrocarbon exploration and logging developments with multiple vested interests may pose additional barriers to carbon projects[16]. Therefore, it is imperative to implement other conservation strategies and interventions, in addition to carbon finance, to safeguard the carbon stocks and biodiversity in these vulnerable forests.

Fig. 3. Effect of carbon pricing on the financial viability of forest carbon sites (i.e. the proportion of investible forest carbon that are financially viable for carbon finance). Shadings around the lines represent confidence bands based on standard deviation.

Obviously, there is a wide range of environmental, socioeconomic, governance and geopolitical factors that can influence climate strategies, conservation actions and investment decisions[17]. For example, some carbon projects may include financially unviable sites that are important for biodiversity conservation, maintaining rural livelihoods or provide other co-benefits of forest protection that may be highly valued by society but not internalized in our analysis[4].

Furthermore, the political ecology landscape of existing and new carbon investments within a host country may also influence the long-term success of forest carbon projects, and ultimately the permanence of carbon credits[9]. For example, the political risk for certified carbon credits has recently increased significantly in Brazil. In exchange for political support, the Brazilian government laid the foundation for landowners to accelerate deforestation[18]. This political bargaining may have seriously compromised Brazil's ability to meet the Paris target. These political risk considerations are crucial to ensure the long-term viability of carbon investments.

Our analyses draw from a sliver of the best available data to provide a snapshot of the relative investible carbon and return-on-investment for the protection of tropical forests as a natural climate solution. By clarifying some of the opportunities and constraints of tropical forest carbon projects, we help to calibrate expectations, incentivize actions, and expedite public and private sector engagements and capital investments in natural climate solutions to benefit the environment, climate and society.

Declarations

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Competing interests: The authors declare no conflict of interest.

Data availability: Validation data are summarized in Table S1. All maps generated are available from corresponding authors upon request.

Code availability: All R scripts used to generate maps are available from corresponding authors upon request.

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Methods

Overview of methods

In this study, we modeled the magnitude of certifiable carbon from forest carbon projects and its climate mitigation potential to produce a global investible forest carbon map. We then compared this estimated volume to that of verified carbon units reported from existing verified projects in the Verra database (https://verra.org/). Lastly, we modeled the relative profitability of these forest carbon sites to produce a global forest carbon return-on-investment map based on their net present value (NPV). All calculations were based on data dated between 2012 and 2017 and at a resolution of 0.00833 degrees (~1 km). To ensure data standardization, we resampled (bilinear) finer-scaled data where necessary, for example, for data sourced from ESA-CCI[19].

Estimating investible carbon

To model and produce a spatially explicit map of investible carbon, we performed two key analyses. The first was to estimate relative above- and below-ground biomass carbon across tropical forest areas:

- To achieve this, we adapted methods from Saatchi et al.[20] and applied them to more recent data (2012–2016). In particular, we based our estimates of aboveground biomass on maps from Avitabile et al.[21] applying a stoichiometric factor of 0.47, which was based on the average value across several reference studies—(e.g.[3,20,22]).
- These maps were constrained to include only tropical forests between ~23.44°N and 23.44°S, and excluding all land cover types that would preclude forests, for example, bare ground, water, agriculture and urban areas[19].
- We then used the aboveground biomass maps from Avitabile et al.[21] to estimate the belowground biomass following the methods of Saatchi et al.[20], which was derived from the root:shoot biomass ratio equation in Mokany et al.[23]: Belowground biomass = $0.489 \cdot \text{Aboveground biomass}^{0.89}$
- We applied the same stoichiometric factor to estimate belowground biomass carbon, and added the organic carbon density of the topsoil layer (0–30cm) obtained from the European Soil Data Centre[24]. This produced an overall belowground biomass carbon estimate.
- Following this, we used a conversion factor of 3.67[3] to estimate the volume of CO_2e associated with both above- and below-ground biomass carbon.

To the above- and below-ground biomass carbon estimates, we applied the key criteria for certifying carbon credits and Voluntary Emissions Reduction units (VERs) under the rules of the UNFCCC, Kyoto Protocol, and the various voluntary certification standards, such as the Verified Carbon Standard (VCS)[8,9]. Importantly, our analyses were guided by the requirements stipulated by VCS—the most widely used voluntary greenhouse gas program globally[8]:

- A key component of the requirements is "additionality" or the amount of forest carbon stocks that would be lost to deforestation without the protection of the proposed project. To estimate additionality, we utilized the average predicted deforestation rates (2029) generated in Hewson et al.[10] annualized over the prediction period (15 years). This produced an estimated annual deforestation rate, which we then multiplied by the above- and below-ground biomass carbon layers to approximate additionality.
- While belowground carbon pool estimates are an optional consideration in VCS, we included them in our study, and calculated a conservative 10-year decay estimate[8].
- Additionally, we further excluded areas that would not qualify as certifiable within these forest areas[8]. These included recently deforested areas (2010–2017)[25] as well as human settlement areas within these forest[26].
- Lastly, we also accounted for VCS requirement to set aside buffer credits of 20% net change carbon stocks in each area[8].

Comparing our investible carbon estimates to verified carbon units

We compared our estimates of investible carbon to the volume of verified carbon units reported by existing verified avoided deforestation projects. We utilized the Verra Project Database (https://verra.org/), extracting all avoided deforestation projects that: 1) possessed project area data; 2) is entirely within the tropics; 3) has been verified. Verified projects here included both the statuses "Verified, under verification" and "Verification approve" (Table S1).

- To compare these data, we first extracted the shapefiles of 28 projects that met these criteria (see Table S1). These shapefiles were then used to extract the corresponding total volume of estimated investible carbon credits via masking.
- We then compared these values to the volume of verified carbon units (VCUs) issued across the years (2005–2018) for each project. The number of yearly data points for each project ranged from 1–13, and generated a total of 134 points of comparison. We then assessed the degree of correlation, with Pearson's correlation, and relative accuracy, via Root Mean Square Error (RMSE), of these corresponding data.

Estimating return-on-investment

Based on our map of investible carbon, we modelled the relative profitability of these forest carbon sites to produce a global forest carbon return-on-investment map. We calculated the NPV of these returns based on several simplifying assumptions following established values from previous studies[14].

- First, we estimated the cost of project establishment at \$25 ha^{-1}. This was based on the a wide range of costs that are key to the development of a project—including but not limited to project design, governance and planning, enforcement, zonation, land tenure and acquisition, surveying and research[14,27,28].
- Second, we estimated an annual maintenance cost of \$10 ha^{-1}, which included aspects such as education and communication, monitoring, sustainable livelihoods, marketing, finance and administration[14,27,28].
- Third, we assumed a constant carbon price of \$5.8 $t^{-1} CO_2e$ for the first five years. This price was based on an average price of carbon for avoided deforestation projects recorded by Forest Trends' Ecosystem Marketplace reports between 2006–2018[6]. After the first five years, we calculated a 5% price appreciation for the subsequent years over a project timeframe of 30 years[14].
- Based on these criteria, we calculated the NPV as well as the accumulated profits over the next 30 years, based on a 10% risk-adjusted discount rate.
- We secondarily calculated NPV based a range of carbon prices, with a maximum of \$100 t^{-1}CO2e matching the cost-effective thresholds from Griscom et al.[2]. Specifically, we considered the carbon price intervals—\$1, \$5, \$10, \$15, \$25, \$50, \$100 $t^{-1} CO_2e$—while maintaining the project establishment and annual maintenance cost, price appreciation, discount rates and timeframe. Based on these criteria and excluding site that unable to breakeven, we then calculated the potential profitable forest areas associated with these carbon prices as a percentage of the total investible forest carbon sites.

These values of investible carbon and return-on-investment (based on NPV) were summarized to global, regional, and country level estimates (see Table 1). While some countries extend beyond tropical latitudes, we only analyze and present data based on their tropical areas. These values were rounded to the nearest 1000 values.

Accounting for uncertainty

To incorporate uncertainty across our estimations, we utilized the uncertainties inherent to the source datasets (reported as standard deviations)[21]. We also estimated the uncertainty associated with the price of carbon, calculating the standard deviations drawn from an assumed uniform distribution with the minimum and maximum price of carbon between 2006–2018. All uncertainty values are reported as standard deviations in the results (Table 1, S1).

All analyses was performed in R version 3.6.0[29], utilizing the package “raster” for processing and calculations of raster layers[30]. Map visualizations were formed in QGIS[31].

Method References

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Figures

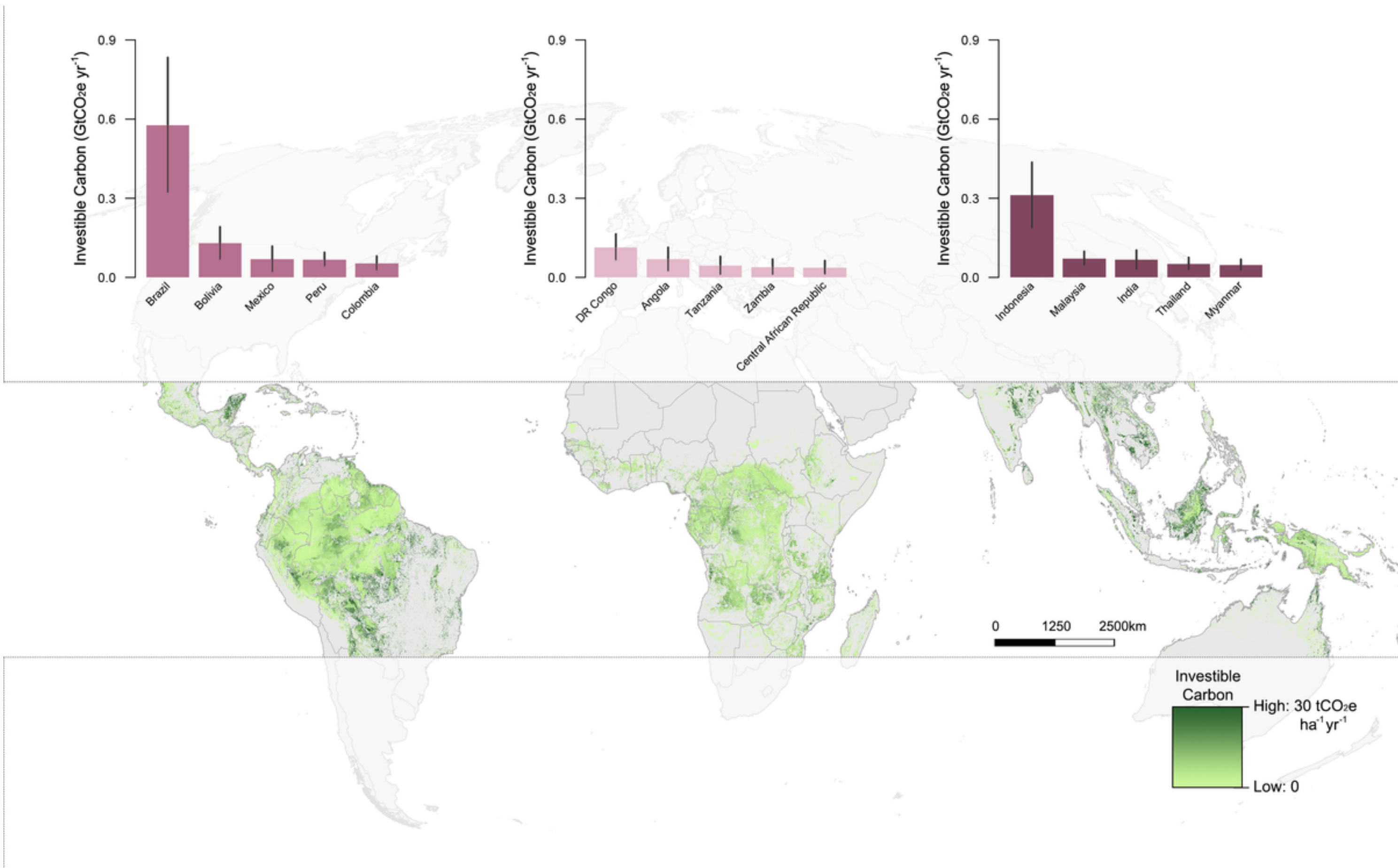

Figure 1

Global investible forest carbon across the tropics, highlighting the estimated volume of investible carbon from the five countries with the highest potential in each of the tropical regions of the Americas, Africa, and Asia-Pacific.

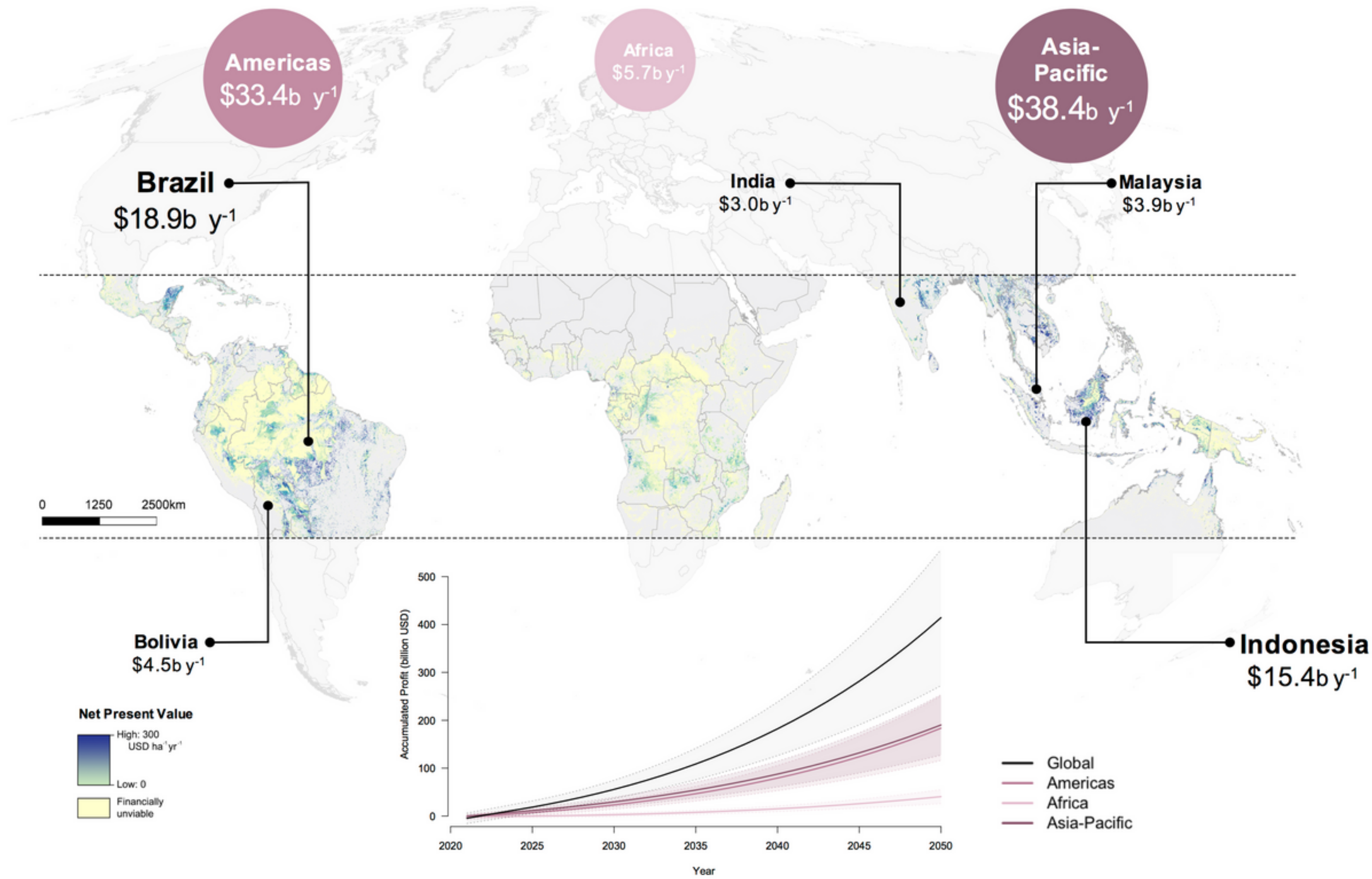

Figure 2

Global forest carbon return-on-investment from financially viable sites, presented as net present values over a 30-year timeframe. We also present the accumulation of profits over time at the global and regional levels (inset).

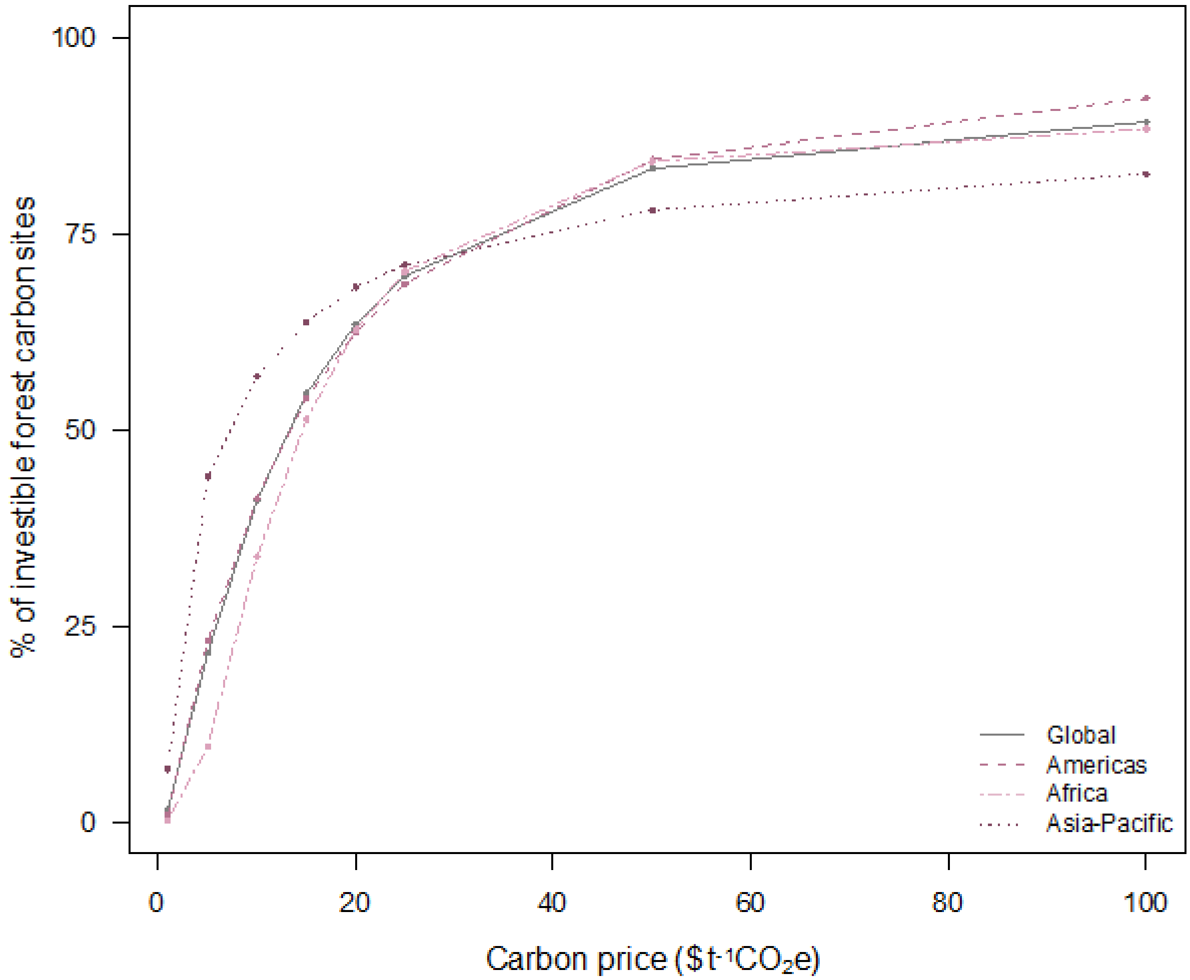

Figure 3

Effect of carbon pricing on the financial viability of forest carbon sites (i.e. the proportion of investible forest carbon that are financially viable for carbon finance). Shadings around the lines represent confidence bands based on standard deviation.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- KohZengSariraSimanFullSupplementaryMaterials21Aug.docx