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A Global Analysis of the Cost-Efficiency of Forest Carbon Sequestration

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Abstract

The paper proposes a ranking of the countries where forest carbon sequestration is the most cost-efficient among 166 countries for which data are available. Taking into account the main cost factors leads to a more nuanced ranking of the countries to be favoured for cost-efficient forest carbon sequestration compared to the assumption that these would always be in tropical areas with high rainfall. The ranking reflects the differences in the opportunity cost of land use and labour cost (production costs), the quality of the business environment (transaction costs), natural conditions (forest productivity), wildfire risk and the avoided GHG emissions from alternative land use. Cost-efficiency also depends on the type of forest project (afforestation, reforestation or forest conservation) and how private (wood harvest) and non-private (environmental and social) co-benefits are counted. A sensitivity analysis is undertaken to examine the robustness of the results with respect to uncertainties in values of the cost and quantity factors of forest carbon sequestration. The results support the view that forests can be a cost-efficient way to offset GHG emissions and that significant cost reductions are possible by targeting the country and sub-national regions in which to locate forest carbon sequestration projects. The report also reviews the literature on the significance and cost of forest carbon sequestration and provides an overview of forest carbon offset schemes.

Keywords: carbon offsets, climate change mitigation, forest co-benefits, forest cost-efficiency, forest carbon capture.

JEL codes: Q23, Q54, Q57, Q58.

Résumé

Le document propose un classement des pays où la séquestration du carbone forestier est la plus rentable parmi 166 pays pour lesquels des données sont disponibles. La prise en compte des principaux facteurs de coûts conduit à un classement plus nuancé des pays à privilégier pour une séquestration rentable du carbone forestier par rapport à l'hypothèse selon laquelle ceux-ci seraient toujours situés dans des zones tropicales à fortes précipitations. Le classement reflète les différences dans le coût d'opportunité de l'utilisation des terres et le coût de la main-d'œuvre (coûts de production), la qualité de l'environnement des affaires (coûts de transaction), les conditions naturelles (productivité forestière), le risque d'incendie de forêt et les émissions de GES évitées résultant d'une utilisation alternative des terres. La rentabilité dépend également du type de projet forestier (boisement, reboisement ou conservation des forêts) et de la manière dont les co-bénéfices privés (récolte de bois) et non privés (environnementaux et sociaux) sont comptabilisés. Une analyse de sensibilité est entreprise pour examiner la robustesse des résultats par rapport aux incertitudes dans les valeurs des facteurs de coût et de quantité de la séquestration du carbone forestier. Les résultats soutiennent l'opinion selon laquelle les forêts peuvent être un moyen rentable de compenser les émissions de GES et que des réductions de coûts significatives sont possibles en ciblant le pays et les régions infranationales dans lesquelles localiser les projets de séquestration du carbone forestier. Le rapport passe également en revue la littérature sur l'importance et le coût de la séquestration du carbone forestier et donne un aperçu des programmes de compensation du carbone forestier.

Mots clés: compensations de carbone, atténuation du changement climatique, co-avantages des forêts, rentabilité des forêts, capture du carbone forestier.

Classification JEL: Q23, Q54, Q57, Q58.

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Executive summary

In December 2015, the twenty-first session of the Conference of the Parties (COP 21) to the UN Framework Convention on Climate Change (UNFCCC) – the Paris Agreement – set a long-term goal of keeping the increase in global average temperatures to well below 2°C above pre-industrial levels. Greater than 2°C temperature increases could have disastrous consequences. Limiting global warming to 1.5°C instead of 2°C would imply significantly reduced risks to terrestrial ecosystems (IPCC, 2019a). The rise in land surface air temperature as well as the increase in the frequency and intensity of climate extremes since the pre-industrial period have already adversely impacted terrestrial ecosystems and have contributed to desertification and land degradation in many regions (IPCC, 2020). Managing climate risks requires mitigation strategies to stop the increase in atmospheric carbon dioxide (CO_2) concentrations.

The seemingly relatively low cost of carbon sequestration by forests has sparked public interest in the potential of forests to offset CO_2 emissions. Key policy questions regarding the cost-efficiency of forest carbon sequestration include: (i) What are the main factors of cost and quantity of forest carbon sequestration? (ii) Should the private and non-private co-benefits of forests be taken into account? (ii) Where are the most cost-efficient places to undertake forest carbon sequestration?

In response to these questions, the paper proposes a framework to assess of the cost-efficiency of forest carbon sequestration using six main factors based on existing databases. It is assumed that the three main cost drivers of carbon sequestration by forests are the opportunity cost of land use as well as the labour costs and transaction costs to implement a forest carbon project (transaction costs are approximated by the ease of doing business indicator). Forest productivity (as estimated by the normalised difference vegetation index), wildfire risk and agricultural GHGs avoided by afforestation are assumed to be the three main factors of net carbon sequestration by forests. The cost-efficiency analysis of carbon sequestration from forests requires taking into account the correlations between these factors of cost and quantity of forest carbon sequestration. For example, high transaction costs can discourage carbon sequestration in countries with high forest productivity. On the other hand, countries with a good quality of business environment often have higher labour costs

The results show very large differences in the cost-efficiency of forest carbon sequestration across countries and between types of forest project (afforestation, reforestation or forest conservation). The findings suggest that geographic targeting and prioritising forest conservation over afforestation would significantly improve the cost-efficiency of forest carbon sequestration. Another important finding is that the countries where the sequestration of forest carbon is the most cost-efficient are practically the same whether considering private co-benefits (wood revenues) or environmental and social co-benefits.

Including the co-benefits of timber harvesting, the average cost of forest carbon in the 50 most cost-efficient countries (top 50) is around USD 4 – 9/tCO_2 via forest conservation and around USD 16 – 25/tCO_2 via afforestation, depending on the level of timber co-benefits, which is 50 to 70% lower than the global average. Considering the environmental and social co-benefits of forests (non-private co-benefits), the global average cost of sequestration can turn negative with values ranging between USD -53 – 2/tCO_2 for forest conservation, USD -28 – 36/tCO_2 for reforestation, and USD 0 – 54/tCO_2 for afforestation, depending on the level of non-private co-benefits. A negative value for the cost means that, at a societal level, non-climate benefits in terms of environmental and social values more than offset the costs of carbon sequestration in forests. The substantial difference in the cost with and without the non-private co-benefits emphasises the role of collective action to promote public benefits in relation to forests.

The results support the view that forest conservation, in general, is more cost-efficient than afforestation because conservation helps avoid large emissions from existing carbon stock that would happen if deforestation were to occur. Afforestation (the conversion from other land uses into forest) also involves a substantial cost at the planting stage and the opportunity costs of land use change can be very high. When considering non-private (environmental and social) co-benefits, a distinction is made between afforestation and reforestation (re-establishment of forest after logging or natural perturbations) due to the possible difference in their non-private benefits. It is assumed that reforestation can potentially restore all the environmental and social co-benefits of the original forests, if the projects are long enough, while afforestation (often with fast-growing species) can only generate part of them. The results show that the cost-efficiency of reforestation is intermediate between forest conservation and afforestation.

The countries/regions where the sequestration of forest carbon is the most cost-efficient are a few African countries, a few Asian countries, many Latin American countries, North America countries, Oceania countries, Eastern Europe, Caucasus and Central Asia (EECCA) countries, Baltic countries, countries of the east of Europe, Ireland and the United Kingdom, i.e. not necessarily tropical areas contrary to popular belief that these would always be the best place to buy low-cost forest carbon credits. Taking into account the main factors of cost and quantity of forest carbon sequestration leads to a more nuanced ranking of the countries to be favoured for cost-efficient forest carbon sequestration.

1. Significance of forest carbon sequestration

Keeping average surface temperature increases to 2°C or less by 2100 is highly unlikely without much greater greenhouse gas (GHG) emissions reductions than business as usual (UNEP, 2021). By reducing the concentrations of carbon dioxide (CO_2) in the atmosphere, forest carbon sequestration can play an important role in climate change mitigation and, thus, reduce the probability of catastrophic climate change impacts. 'Natural climate solutions' -- including forest carbon sequestration -- could provide around a third of the cost-effective CO_2 mitigation needed through to 2030 to avoid crossing a 2°C average global surface temperature increase (Federici et al., 2015; Griscom et al., 2017).

Forest carbon sequestration is viewed by many as a cost-effective solution to control the increase in CO_2 concentrations in the atmosphere (Richards, Moulton and Birdsey, 1993; Parks and Hardie, 1995; Bruce, Lee and Haites, 1996; Stern et al., 2007; Bosetti et al., 2011; Michetti and Rosa, 2012; Gren and Aklilu, 2016). In particular, the cost of sequestrating carbon in forest-based projects could be 40% lower when compared to other approaches (De Jong, Tipper and Montoya-Gómez, 2000; Tang, Yang and Bian, 2014). This is because the average cost per unit emission reductions of renewable energy could be more than twice as high as the cost of forest carbon sequestration (Knopf et al.,2013; Vass, 2017) while new technologies, such as direct capture of CO_2 from the air (Pielke, 2009; Keith et al., 2018), are several times more expensive than cost-effective methods of forestry carbon sequestration.

Forest-based sequestration projects are likely to play a substantial role in climate change mitigation in the short to medium term. In the long-term, e.g. after 2050, forest-based sequestration may be less cost-effective to alternatives (Minx et al., 2018). In particular, other methods of sequestration, such as bioenergy with carbon capture and storage (BECCS) and direct air carbon capture and storage, may be more cost-effective (Minx et al., 2018).

1.1. FAO Global Forest Resources Assessment

According to the FAO, although the forests of Annex I countries to the UN Framework Convention on Climate Change (UNFCCC), including OECD countries, have always been a net carbon sink since 1990, the world's forests have been a net carbon source of about 0.3 $GtCO_2$ (0.1 GtC)[1] annually during the period from 2016 to 2020, mainly due to tropical deforestation.[2] The Global Forest Resources Assessment 2020 (FAO, 2020) estimates that the global forest area declined by some 4% (178 million has) since 1990 to stand at around 4 billion has in 2020.

The annual rate of net forest loss, however, was reduced from 7.8 million has (Mha)/year in 1990-2000 to 5.2 Mha/year in 2000-10 and 4.7 Mha/year in 2010-20. The rate of forest loss has decreased due to reduced deforestation, afforestation and natural forest expansion. Most (45%) of the remaining forest area

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[1] 1 tC is equivalent to 3.67tCO_2.

[2] http://www.fao.org/faostat/en/#data/GF/visualize, accessed 31 May 2021.

is tropical forests, the remainder being boreal forests (27%), temperate forests (16%) and subtropical forests (11%). The world still has around 1 billion has of primary forest (i.e. naturally regenerated forests of native tree species). The area of primary forest has declined by 81 Mha since 1990, though the rate of loss has more than halved in 2010-20 compared to the previous decade. Since 1990, the area of planted forests (that is, forests mainly composed of trees established through planting) has increased by 123 Mha.

Africa recorded the highest annual net forest loss rate in 2010-20, with 3.9 Mha, followed by South America, with 2.6 Mha (FAO, 2020). The rate of net forest loss has steadily increased in Africa since 1990, while it halved in South America between 2000–10 and 2010–20. Asia recorded the highest net gain in forest area in 2010–20, followed by Oceania and Europe.

Most of the world's terrestrial carbon is stored in forests. Forests cover about 31% of the land surface and hold almost half of the world's terrestrial carbon. The world's total carbon stock of forests, including living biomass and soil organic matter, has declined slightly since 1990, from 668 gigatonnes (Gt) in 1990 to 662 Gt in 2020 (FAO, 2020). It reflects the slight decrease in the world's total growing stock of trees (i.e. the volume of all living trees), from 560 billion m^3 in 1990 to 557 billion m^3 in 2020, due to a net decrease in forest area.

1.2. Types of forest carbon sequestration projects

There are two broad types of forest-based carbon sequestration projects, namely (i) Afforestation and Reforestation (A&R) and (ii) forest conservation which includes Improved Forest Management (IFM) and Reducing Emission from Deforestation and Forest Degradation (REDD+).[3]

1.2.1. Afforestation and Reforestation (A&R)

A&R are activities whereby trees are planted on land which has not recently been forested. The benefit in terms of climate change mitigation is that the planted and growing trees are able to sequester carbon in living biomass and the soil (Laganiere, Angers and Pare, 2010).

For above-ground biomass, the rate of carbon sequestration in forest biomass depends on tree species, site conditions, tree density and rotation. Following afforestation, this rate follows a sigmoidal pattern, increasing to a maximum and then decreasing as the forest approaches maximum biomass. The maximum biomass is mainly a function of site conditions (climatic and soil conditions). Different species follow different growth patterns. Faster growing species can sequester carbon more rapidly (although this depends on wood density) but may have shorter life spans and lower maximum biomass (Dutcă, Abrudan and Blujdea, 2009). Secondary tropical forests (i.e. natural recovery of aboveground biomass after removal of forest cover for agricultural purposes) can sequester carbon at a rate of 0.4-6.3 tC/ha/year for the first 20 years of natural regrowth (Silver, Ostertag and Lugo, 2001; Poorter et al., 2016). The above-ground carbon sequestration rate of oak forests in Denmark, Sweden and Netherlands ranges between 2.7 and 4.6 tC/ha/year, which is similar to the average rates of 4.1 tC/ha/year for temperate forests (Winjum and Schroeder, 1997). For conifer forests, the carbon sequestration rate following afforestation can be up to 10t/ha/year in Australia and New Zealand, 1.5-4.5 tC/ha/year in Europe and the United States, 0.9-1.2 tC/ha/year in Canada and Russia, and 6.4-10 tC/ha/year in tropical Asia, Africa and Latin America (Dutcă, Abrudan and Blujdea, 2009). CGDD, 2019 estimates the current carbon sequestration of the metropolitan France forest (two thirds of deciduous trees, one third of conifers) at 5.06 tCO_2e/ha/year (1.4tC/ha/year); the French Guyanese rainforest is estimated to be in equilibrium (no carbon sink, no emissions).

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[3] REDD (with the plus) refers to reducing emissions from deforestation and forest degradation (REDD) *and* enhancing forest carbon stock.

Soil carbon after afforestation and reforestation depends on many factors, such as previous land use, climate, tree species planted (Paul et al., 2002), plant productivity, soil physical and biological properties, the history of carbon inputs and physical soil disturbance (Post and Kwon, 2000). Afforestation may result in either a decrease or increase of soil carbon depending on the previous land use. Establishing forest plantations on grazing lands generally results in a loss of soil carbon over the first 5-10 years after afforestation, but the initial carbon balance can be restored after 30 years (Paul et al., 2002). Establishing forests on former cropping land usually increases soil carbon in the short term (within the first 10 years).

1.2.2. Improved Forest Management (IFM)

IFM includes activities such as increasing timber cutting time, increasing minimum harvestable tree size, improving forest or soil productivity, leaving *in situ* some of the woody increment (trees in growth period) that could be harvested under standard forest management or reducing the impact of forest harvesting (Vacchiano et al., 2018). IFM can increase average carbon stocks relative to unmanaged forests so that more carbon is sequestered compared to business-as-usual management. When production forests are harvested, some carbon is emitted immediately, some decays over time in wood left on the site, and some carbon is stored in wood products (Pilli, Fiorese and Grassi, 2015). The duration of carbon storage depends on the type of product. Assessing the carbon dynamics of a production forest estate can include estimates of wood product stocks (Pukkala, 2017). Further, substituting wood for energy-intensive materials such as steel and cement can also reduce carbon emissions (Sathre and O'Connor, 2010). On the other hand, harvesting forests primarily for the production of fuel pellets or other short-lived products leads to significant short-term CO_2 emissions (when these products are consumed), which the regrowth of the harvested forest takes several decades to offset.

FLUXNET data[4] demonstrate that old-growth forests, including boreal and temperate forests, can continue to accumulate carbon, contrary to the long-held view that they are carbon neutral (Luyssaert et al., 2008). The general trend is that rates of net carbon sequestration slow as forests age, but there appears to be no set number for the age at which a steady state carbon balance is achieved. The age varies between deciduous and evergreen forests (Xu et al., 2020).

1.2.3. REDD+

The concept of paying to avoid deforestation was initiated at the Conference of the Parties (COP) 11 in 2005 and the Reducing Emissions from Deforestation and Forest Deforestation (REDD+) framework was *codified in the 2013 Warsaw Framework* and included in the 2015 Paris Agreement. REDD+ projects related to the 'plus' include conservation, sustainable management of forests, and enhancement of forest carbon stocks. Estimated global expenditures to respond to deforestation and to protect forests in tropical countries since 2010 is some USD 3.2 billion (NYDF Assessment Partners, 2019).

To date, payments for REDD+ programmes and projects have been funded by: (1) donors who contribute to a fund managed by a multilateral or donor agency (for example the World Bank); (2) donors who contribute directly to a recipient country through bilateral agreements and from the private sector through voluntary offset activities. Many REDD+ payments have been sponsored by governments, including Norway, Germany, Australia, the United States and the United Kingdom (UK). Private or public organisations are also contributors, such as BP Technology Ventures and the non-profit The Nature Conservancy, both of which have contributed to the World Bank-managed Forest Carbon Partnership Facility's Carbon Fund (Hamrick and Gallant, 2017a). Much of the finance to date has focused on building

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[4] FLUXNET is a global network of micrometeorological tower sites that use eddy covariance methods to measure the exchanges of CO_2, water vapour, and energy between terrestrial ecosystems and the atmosphere. More than 500 tower sites around the world are operating on a long-term basis.

capacity and technical capabilities for countries to participate in REDD+ (REDD+ readiness), rather than payments for achieved emissions reductions.

International donors have pledged a cumulative USD 4.1 billion in payments for REDD+ with much of it for preparation and implementation (Climate Focus, 2017). The committed funding under the FCPF Carbon Fund and Initiative for Sustainable Forest Landscapes, as well as the USD 500 million GCF pilot programme, are destined for results-based payments. All voluntary payments are for verified emissions reductions, not capacity building. It is important to clearly distinguish between REDD+ finance, public results-based payments, and carbon offset transactions. One of the largest pledges is from the Green Climate Fund that has committed to pay USD 500 million for REDD+. The fund is now seeking applications from countries that have active REDD+ programmes and have successfully avoided deforestation between 2014 and 2019. The World Bank's Forest Carbon Partnership Facility includes 18 countries, several of which have already signed Emission Reduction Purchase Agreements (Hamrick and Gallant, 2017a).

1.3. Forest sequestration by carbon pool and forest type

There are four main carbon pools in forests: (1) above ground living biomass; (2) litter; (3) dead wood and (4) soil organic matter (below-ground biomass). Globally, most of forest carbon is found in living biomass (44%) and soil organic matter (45%), with the remainder in litter (6%) and dead wood (4%) (FAO, 2020). Estimates of global carbon sequestration in these pools of terrestrial ecosystems range from less than 1 GtC/year to as much as 2.6 GtC/year (IPCC, 2007).

Research results synthesised by Pan et al., 2011 show that global carbon uptake by established forests was 2.5±0.4 GtC/year for the period 1990 to 1999, and 2.3±0.5 GtC/year over the period 2000 to 2007 (Table 1). Carbon uptake varies substantially between biomes, with tropical intact forests being the most effective (Table 1). Between 1990 and 2007, tropical deforestation wiped out more than half of the world's forest carbon sequestration (Table 1).

Table 1. Carbon sequestration by forest type (GtC/year)

Carbon sink and source in biomes	1990-99	2000-07	1990-2007
Boreal forest	0.50 ± 0.08	0.50 ± 0.08	0.50 ± 0.08
Temperate forest	0.67 ± 0.08	0.78 ± 0.09	0.72 ± 0.08
Tropical intact forest	1.33 ± 0.35	1.02 ± 0.47	1.19 ± 0.41
Total sink in global established forest	*2.50 ± 0.36*	*2.30 ± 0.49*	*2.41 ± 0.42*
Tropical regrowth forest	1.57 ± 0.50	1.72 ± 0.54	1.64 ± 0.52
Tropical gross deforestation emission	-3.03 ± 0.49	-2.82 ± 0.45	-2.94 ± 0.47
Tropical land-use change emission	*-1.46 ± 0.70*	*-1.10 ± 0.70*	*-1.30 ± 0.70*
Global net forest sink	1.04 ± 0.79	1.20 ± 0.85	1.11 ± 0.82

Source. Pan et al., 2011.

1.4. Forest carbon sequestration capacity

Tavoni, Sohngen and Bosetti, 2007 estimate the global carbon sequestration potential of forest management in different countries and regions until the end of the century (Table 2). Their results show that forests could sequester around 75 GtC cumulative between 2000 and 2050 (i.e. 1.5 GtC/year), mostly from avoided deforestation in tropical-forest-rich countries. According to Tavoni, Sohngen and Bosetti, 2007, most of the carbon sequestration is expected to occur in non-OECD countries until 2022 (Table 2). Subsequently, the potential for sequestration would be more balanced between the OECD and non-OECD areas, as there would no longer be opportunities to reduce deforestation in the latter, where forest growth on the vast area of land reforested during the century would start to slow (ibid).

Table 2. Regional potential carbon sequestration of forest management (MtC/year)

Country/region	2022	2052	2092
OECD and South Africa			
United States	42	144	193
Europe part I[1]	37	82	132
Europe part II[2]	8	18	29
Canada, Japan, New Zealand	31	115	125
Korea, South Africa, Australia	25	27	36
Total OECD and South Africa	**143**	**387**	**515**
Non-OECD			
Transition economies	179	117	134
Middle East and North Africa	73	49	31
Sub-Saharan Africa	270	175	106
India, South Asia	34	57	32
China	109	155	431
South East Asia	451	481	371
Latin America and Caribbean	391	326	330
Total non-OECD	**1 624**	**1 719**	**1 914**
Total global	**1 766**	**2 105**	**2 429**

Note: [1] Belgium, France, Germany, Italy, Luxembourg and the Netherlands.
[2] Austria, Czech Republic, Denmark, Estonia, Finland, Greece, Hungary, Ireland, Latvia, Lithuania, Poland, Portugal, Slovenia, Spain, Sweden and the United Kingdom.
Source: Tavoni, Sohngen and Bosetti, 2007.

Griscom et al., 2017 estimate the global potential for carbon sequestration by forests to be much higher, around 16 $GtCO_2$ (4.4 GtC) per year by 2030, mainly through reforestation;[5] half would be cost-effective with a social cost of carbon of USD 100/Mt CO_2e. Unlike Tavoni, Sohngen and Bosetti, 2007, Griscom et al., 2017 consider soil carbon sequestration. However, the amounts of carbon lost or gained by soil following afforestation are generally low compared to the accumulation of carbon in above-ground biomass (Paul et al., 2002).

Busch et al., 2019 estimate that an increase in the carbon price from USD 20/tCO_2 to USD 50/tCO_2 would increase global forest sequestration from 5.7 to 15.1 $GtCO_2$ over the 2020-50 period. Austin et al., 2020 project a mitigation potential of the global forest sector of 0.8 to 6.0 $GtCO_2$ (0.2-1.6 GtC)/year over the period 2015-55 with an initial carbon price of, respectively, USD 5-100/tCO_2, assuming an annual growth rate of carbon prices of 3%. The largest share of global forest sector mitigation (72-82%) would come from the tropics (ibid). FAO's assessment of forest resources shows that deforestation has still not been reduced in non-OECD countries (see section 1.1), which may suggest a more uncertain future than predicted.

1.5. Forest carbon sequestration costs

The cost of forest carbon sequestration varies greatly by location and project. This large variation arises from several factors. First, there are multiple ways to sequester carbon through forestry (FAO, 2004. Thus, costs vary in relation to how the carbon is sequestered. Second, the carbon sequestration of a project is

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[5] Food security, fibre security and biodiversity conservation constraints are taken into account.

evaluated by how much carbon is sequestered *in addition to what would happen without the project*. Thus, critical to the calculations is additionality and what are the baseline assumptions (De Jong, Tipper and Montoya-Gómez, 2000). Third, the cost varies depending on the duration of the project (Stavins, 1999), e.g. afforestation projects likely sequester less carbon in the first five years than the second five years, even with similar cost, because of tree growth cycles. Fourth, data limitations exist in relation to both the cost and the amount of carbon sequestered by a project. Fifth, costs of forest-based carbon sequestration vary greatly depending on the methods used and modelling assumption (Richards and Stokes, 2004; Stavins and Richards, 2005; van Kooten and Sohngen, 2007), and whether co-benefits are included (Nielsen, Plantinga and Alig, 2014). Different assumptions, in particular, about carbon uptake of trees, age of the forest stock, tree species, geographic location, site attributes, the disposition of forest products, among other factors (van Kooten and Sohngen, 2007), also have a major influence on the estimated carbon sequestered.

Richards and Stokes, 2004 review the cost of forest-based carbon projects at various scales. At a global scale, the range is between 0.1 and 188 USD/tC (USD 0.03–51/tCO$_2$) (Table 3). This can be compared to the global estimate of Sedjo and Solomon, 1989 of between USD 3.5 and 7.0/tC (USD 1–2/tCO$_2$) and that of Nordhaus, 1991, of USD 42 to 114/tC (USD 11–31/tCO$_2$), which considers the opportunity cost of land use. Van Kooten and Sohngen, 2007 reviewed findings from 68 studies and 30 countries. They found that the average cost of forest-based carbon sequestration is some USD 88/tC (USD 24/tCO$_2$) (2005 value), but individual estimates range from USD 0.46 to some 1 800/tC (USD 0.1 to 490/tCO$_2$). In another review of projects around the world, Tang et al., 2016 conclude that the cost estimates vary between USD 3 and 130/tCO$_2$ in 2012 depending on the mitigation strategies and locations. Differences in the types of forest carbon sequestration projects, the reference levels used to measure additionality, the scales of projects analysed, the methods for estimating the cost and outcomes of forest projects, among other factors, could explain such a wide variance in the average cost of forest carbon sequestration globally.

Table 3. Average cost of carbon sequestration in forest-based projects

Scale		Cost range[1]	
		(USD/tC)	(USD/tCO$_2$)
Global		0.1–188	0.03–51
Climate zone	Temperate	1–23	0.3–6
	Tropical	1–9	0.3–2.5
Region	South America	4–41	1–11
	Africa	4–69	1–19
	South Asia	2–66	0.5–18
	North America	1–6	0.3–1.6
Country	United States	0–664	0–181
	Canada	6–23	1.6–6
	British Columbia	0–50	0–14
	Netherlands	1 810–6 070	493–1 654
	Tanzania	(3.40)–34.38	(0.9)–9.4
	Mexico	0–40	0–11
	India	0.09–1.22	0.02–0.3
	China	(12)–2	(3.3)–0.5
	Thailand	(579)–12.5	(158)–3.4
	Argentina	20	5.4
	Costa Rica	10–30	2.7–8.2

Note: 1. Considering cost of carbon sequestration in forest plantation, forest management and agroforestry; figures in parentheses indicate negative costs.
Source: Extracted from Richards & Stokes, 2004.

Estimates by Richards and Stokes, 2004 show lower forest carbon sequestration costs in tropical areas compared to temperate areas. According to Manley, 2002, other things being equal, forest carbon projects in the tropics can be half the cost in temperate regions. Raihan et al., 2019 highlight the faster rates of tree growth and carbon sequestration in the tropics. Moura Costa et al., 1999 show that forest carbon projects in developing countries are generally less costly due to relatively low opportunity and labour costs.

In addition to estimates from Richards and Stokes, 2004, there are multiple studies on forest carbon sequestration costs in different countries. For example, Dixon et al., 1994 estimate the costs range from USD 4 to 41/tC (USD 1–11/tCO_2) in Brazil. Masera, Bellon and Segura, 1995 provide an estimate between USD 10 and 35/tC (USD 3–10/tCO_2) in Mexico which is also consistent with the estimate of USD 15/tC (USD 4/tCO_2) by De Jong, Tipper and Montoya-Gómez, 2000. Stavins and Richards, 2005 estimate a cost range from USD 25 to 90/tC (USD 7 to 25/tCO_2) in the United States while Tang, Yang and Bian, 2014 estimate the cost would be less than USD 10/tC (USD 3/tCO_2) in China. Valatin, 2019 reports long-term cost estimates (by 2 200) in the United Kingdom ranging from GBP 21/tCO_2 to GBP 245/tCO_2 (USD 30–346/tCO_2) depending on the type of forest created (e.g. lowland conifers versus broadleaved woodland managed for timber and carbon).

2. Review of forest carbon offset markets

Forest-based carbon offsets developed following (in response to) the 1997 Kyoto Protocol to the UNFCCC. They can be separated into two types of markets: (i) offsets available on the voluntary market and (ii) offsets used for compliance purposes. Voluntary forest carbon offset markets require a willing seller and a willing buyer and there is no regulatory requirement for the parties to enter into a contractual agreement. At present, there is no global, central market and no central regulatory authority that governs the issuers of voluntary offsets. Further, there is less than fully effective emissions accounting at a national level and the potential exists for 'double-counting' of emissions that may undermine carbon markets (Schneider et al., 2019).

The transactions in the voluntary offset sector are private and are often facilitated by brokers. Consequently, there is a wide variance in voluntary forest carbon offset prices that reflect differences in perceived quality and the bundling of co-benefits. Importantly, many of the voluntary offsets include co-benefits in addition to carbon sequestration. These co-benefits may include protection of biodiversity, promotion of gender equality, economic opportunity, aid for displaced peoples, among other benefits. A detailed description of carbon voluntary markets is provided in Annex A.

Compliance markets further developed in the 2000s with the implementation of GHG emission trading systems. In many compliance markets, there are upper limits to which carbon offsets can be used to substitute for emissions reductions. A detailed description of some of the leading compliance markets is provided in Annex B.

Until 2014, voluntary markets had higher trading volumes than compliance markets. The situation has been reversed since 2015; 340 $MtCO_2e$ were traded on compliance markets against 145 $MtCO_2e$ on voluntary markets in 2015-19 (see sections 2.2 and 2.3). OECD countries (United States, Canada, Australia, New Zealand, Japan, Korea, Switzerland) and China are the most active in compliance markets. In contrast, non-OECD countries (especially Latin America) generate the greatest amount of voluntary carbon offsets.

2.1. Criteria to generate a forest carbon offset

To trade forest carbon offsets, several criteria, typically, need to be satisfied. These criteria, in relation to tradable forestry carbon offsets, include that they be: (1) real; (2) permanent; (3) quantifiable; (4) verifiable; (5) unique; (6) transparent; (7) conservative; (8) account for leakage, and (9) be additional (see Box 1).

Box 1. Criteria to generate a forest carbon offset

Real: This is generally interpreted to mean that offsets will not be generated from inaccurate accounting or modelling artefacts.

Permanent: Especially with forest carbon projects there is risk that pests, disease or fire may reverse the gains in stored carbon. Registries for these offsets generally require that there be insurance, a buffer or some other mechanism to make up for potential loss.

Quantifiable: There should be an established methodology that sets a baseline for business-as-usual so that the amount of stored carbon can be estimated in a way that is consistent across projects.

Verifiable: Projects need to have carbon storage verified by third-party experts.

Unique: An offset should only be registered with a single registry to avoid double-counting when the offsets are retired.

Transparent: The methodology for calculating baselines, ensuring additionality and managing for leakage should be clear.

Conservative: When choosing a baseline for business-as-usual a conservative estimate should be made that does not exaggerate the potential for carbon sequestration.

Leakage: Leakage occurs when emissions that would have happened within the project area get shifted outside of the area as a consequence of implementing the offset methodology. There has to be a plan for mitigating or discounting the offsets generated when there is leakage.

Additionality: This criterion requires that the emissions sequestered by the project above the baseline would not have happened without the incentive of the offset payment. That is, it cannot be because it would have been profitable to do so without the offset nor can the changes be part of an effort to meet government regulations.

All of the forest carbon offset schemes described below, whether used through voluntary approaches or in compliance markets, meet these requirements.

A/R protocols typically require that the designated project land *not* be in forest for a defined period of time prior to commencement of the forest carbon sequestration project. A/R protocols, typically, also limit the amount of surface disturbance when establishing a new forest stand.

IFM protocols often require that rotation ages be extended, or certain thinning practices be adhered to over the life of the project. This most commonly requires a conservation easement of some kind to prevent activities on the landscape that could release the stored carbon in the biomass in the project area.

REDD+ emphasises co-benefits that can include poverty alleviation, improved governance, biodiversity conservation and protection of ecosystem services. REDD+ is not managed by one offset issuing agency and operates within the UNFCCC.

2.2. Compliance markets

The period 2015-19 saw a significant increase in compliance forest credits, both in absolute amount and in global market share (World Bank, 2020).[6] The forestry sector represents the largest share (42%) of

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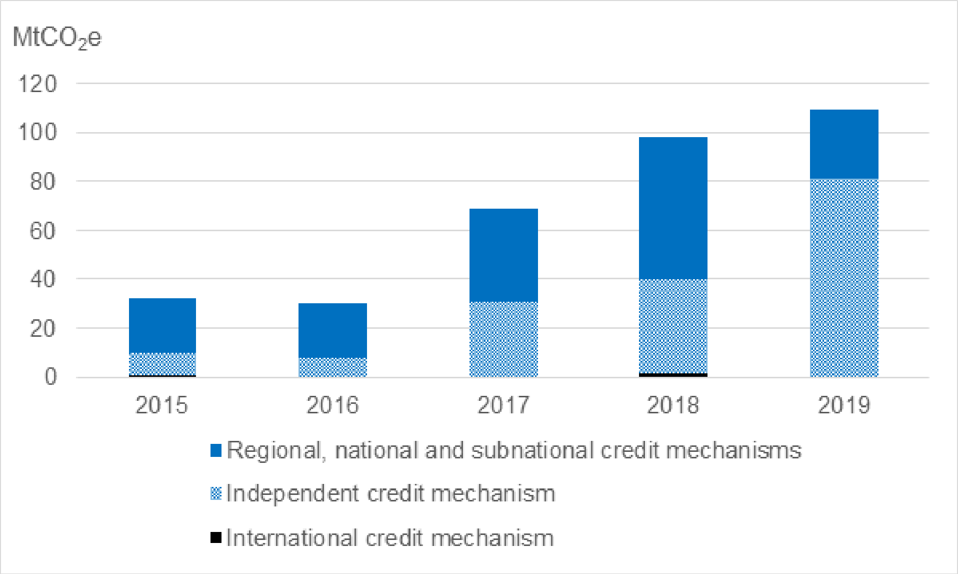
[6] Prior to the recent surge in forestry projects, most crediting activities stemmed from the industrial gas sector.

compliance carbon credits issued over the period, with forestry credits [340 million tonnes carbon dioxide equivalent ($MtCO_2e$) in 2015-19]

Compliance forest credit trading has increased since 2015 relying mainly on regional/national/sub-national credit mechanisms and independent mechanisms, which have overtaken international credit mechanisms (Clean Development Mechanism and Joint Implementation Mechanism under the Kyoto Protocol) (Figure 1). Regional, national and subnational mechanisms issue carbon credits that can be used as part of mandatory carbon pricing initiatives. Independent carbon crediting mechanisms can also generate compliance credits, although they are mainly used for voluntary offset purposes - by organisations and individuals - and constitute the bulk of the voluntary carbon offset credit market.

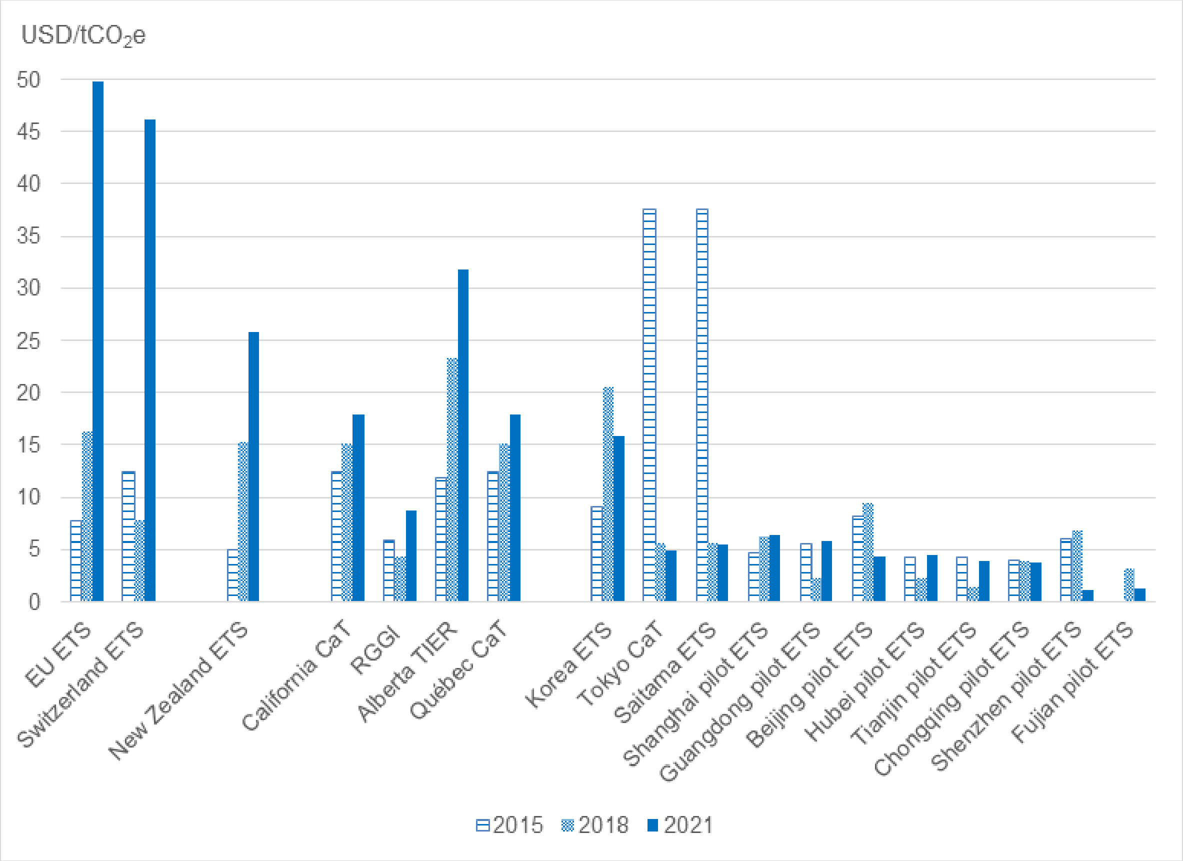
Figure 1. Forest credit trading in compliance markets



Source: World Bank's carbon pricing dashboard (database), https://carbonpricingdashboard.worldbank.org/, accessed 30 May 2021.

With the exception of China, Korea and Japan, the increase in forest carbon trading has occurred against a backdrop of rising carbon prices which has made offsetting more attractive for compliance sectors (Figure 2). Most compliance markets do not currently accept REDD+ offsets from projects or government-run programmes or allow for trade of permits across borders (Goldstein and Ruef, 2016).

Figure 2. Carbon pricing in compliance markets



Note: ETS = Emissions Trading System; CaT = Cap-and-Trade; TIER = Technology Innovation and Emissions Reduction Regulation; RGGI = Regional Greenhouse Gas Initiative.
Source: World Bank's carbon pricing dashboard (database), https://carbonpricingdashboard.worldbank.org/, accessed 30 May 2021.

Forest project carbon credits tend to be popular with project developers and credit buyers because they offer better value for money and generate co-benefits (such as biodiversity conservation) that are more visible than climate change mitigation (World Bank, 2020). Since the creation of compliance carbon credit systems with the Kyoto Protocol in 1997, forest carbon offsets have represented 17% of total offsets in global compliance markets (Table 4).

Table 4. Cumulative carbon credits issued in compliance markets to 2019

Crediting mechanism	Geographic coverage	Year created	Volume ($MtCO_2e$)	
			total	forestry
International[1]			2 874	212
Clean Development Mechanism (CDM)	Global	1997	2 002	160
Join Implementation Mechanism (JI)	Global	1997	872	52
Independent[2]			626	201
Verified Carbon Standard (VCS)	Global	2005	410	172
Climate Action Reserve (CAR)	North America	2001	69	17
American Carbon Registry (ACR)	Global	1996	50	10
Gold Standard	Global	2003	97	2
Regional, national and subnational[3]			523	267
California Compliance Offset Program	State of California (United States)	2013	169	135
New Zealand Emissions Trading Scheme (NZ ETS)[4]	New Zealand	2008	132	83
Emissions Reduction Fund (ERF)[5]	Australia	2012	72	40
British Columbia Offset Program	Province of British Columbia (Canada)	2016	6	5
Fujian Forestry Offset Crediting Mechanism	Province of Fujian (China)	2017	2	2
Alberta Emission Offset System	Province of Alberta (Canada)	2007	56	1
Switzerland CO_2 Attestations Crediting Mechanism	Switzerland	2012	2	1
Beijing Forestry Offset Mechanism	Municipality of Beijing (China)	2014	0.2	0.2
J-Credit Scheme	Japan	2013	6	0.1
Guangdong Pu Hui Offset Crediting Mechanism	Province of Guangdong (China)	2017	1	0.04
China GHG Voluntary Emission Reduction Program[6]	China	2014	53	0.01
Saitama forest absorption certification system	Saitama Prefecture (Japan)	2010	0.01	0.01
Korea Offset Credit Mechanism[7]	Global	2015	16	0
Saitama Target Setting Emissions Trading System	Saitama Prefecture (Japan)	2011	6	0
Québec Offset Crediting Mechanism[8]	Province of Québec (Canada)	2013	0.8	0
Tokyo Cap-and-Trade Program (Tokyo CaT)	Tokyo Prefecture (Japan)	2010	0.5	0
Regional GHG Initiatives (RGGI) CO_2 Offset Mechanism[9]	7 States (United States)	2005	0.05	0
Joint Crediting Mechanism (JCM)[10]	17 non-OECD countries	2012	0.03	0
Total			**4 023**	**680**

Note:
1. Under the Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC); the European Union Emissions Trading System (EU-ETS) has the highest demand for CDM and JI credits, but does not accept credits from forestry projects
2. See Annex A for more details.
3. See Annex B for more details.
4. Domestic carbon credits only (called New Zealand Units - NZU); from 2008 to mid-2015, the NZ ETS accepted imported Kyoto credits (CDM/JI) subject to some restrictions on sources but not on quantities.
5. The ERF is both a voluntary offset instrument [the fund purchases Australian Carbon Credit Units (ACCUs) to support Australia's international commitments] and a compliance offset mechanism that allows large emitters to purchase ACCUs to keep their emissions below a reference level (ERF - Safeguard).
6. Chinese Certified Emission Reductions (CCERs) can be used by compliance entities under Chinese ETS to help meet emission obligations.
7. Korea GHG Emissions Trading Scheme (KETS) allows the use of international credits (CDM) up to 5% of the entity’s emissions submissions.
8. Québec ETS has linked with California’s through the Western Climate Initiative but does not allow offsets from forestry. To increase the offset offer, a new protocol is being developed to allow carbon sequestration through afforestation and reforestation on private land in Québec.
9. Offsets are allowed for 3.3% of entity (electricity producer) liabilities; credits can be issued for forestry activities but there has not yet been a forest offset registered in the market which covers 7 states of the Northeast and Mid-Atlantic.
10. Administered by Japan.
Source: World Bank, 2020; New Zealand’s Environmental Protection Authority website[7].

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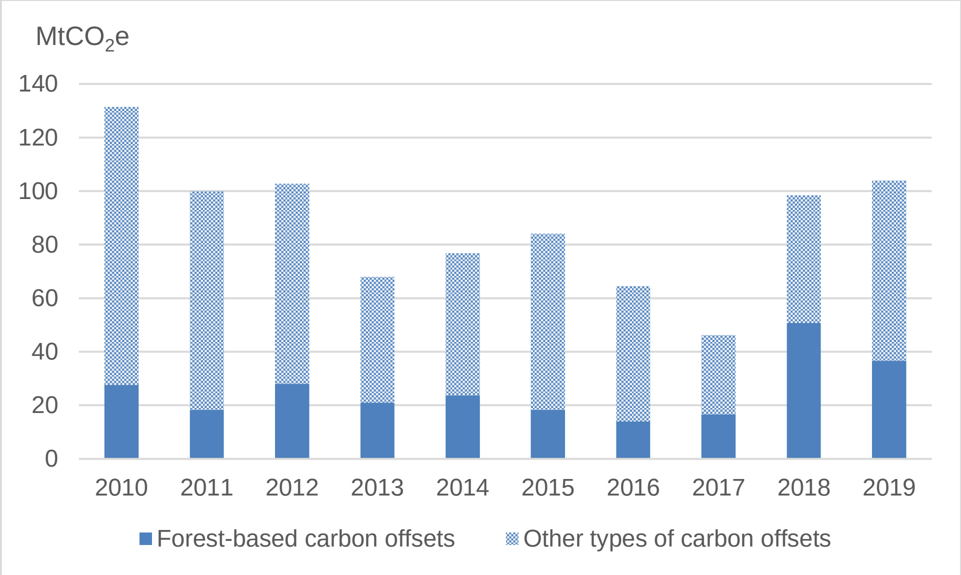
[7] https://www.epa.govt.nz/industry-areas/emissions-trading-scheme/ets-reports/unit-movement/, accessed 29 May 2021.

2.3. Voluntary markets

Forest-based voluntary carbon offsets trading also expanded substantially in 2015-19, albeit in lower volumes [145 $MtCO_2e$ traded in 2015-19]. Between 2010 and 2019, the forestry sector accounted for between 25% and 50% of global voluntary carbon offsets in volume (Figure 3).

Figure 3. Total global voluntary carbon offsets and forest-based carbon offset volume



Source: Peters-Stanley et al., 2011; Diaz, Hamilton and Johnson, 2011; Peters-Stanley and Hamilton, 2012; Kossoy and Guigon, 2012; Peters-Stanley and Yin, 2013; Peters-Stanley and Gonzalez, 2014; Goldstein and Gonzalez, 2014; Goldstein and Neyland, 2015; Hamrick, 2015; Hamrick and Goldstein, 2016; Goldstein and Ruef, 2016; Hamrick and Gallant, 2017a; Hamrick and Gallant, 2017b; Donofrio et al., 2019.

In 2010-16, Latin America captured the lion's share of voluntary forest carbon offsets (Table 5). Over this period, half of the voluntary compensation projects were REDD + projects, the other half being shared between A&R and IFM projects.

Table 5. Total voluntary forest carbon offsets transacted by region

Location	Volume ($MtCO_2e$)							
	2010	2011	2012	2013	2014	2015	2016	Total
Africa	2	5	3	6	4	3	3	25
Asia	4	2	5	3	6	5	2	26
Europe	0.2	1	0.2	0.5	3	0.3	0.3	5
Latin America	17	8	6	18	11	5	5	70
North America	5	7	7	3	5	1	1	28
Oceania	1	2	6	2	5	0.3	0.4	17
Total	**29**	**24**	**27**	**29**	**32**	**14**	**12**	**170**

Source: Adapted from Diaz, Hamilton and Johnson, 2011; Kossoy and Guigon, 2012; Peters-Stanley and Yin, 2013; Goldstein and Gonzalez, 2014; Goldstein and Neyland, 2015; Goldstein and Ruef, 2016; Hamrick and Gallant, 2017a.

2.4. Co-benefits of forest carbon offsets

Co-benefits represent the benefits of forest carbon projects beyond the benefits of carbon sequestration. In addition to regulating the climate (local and global), forests provide many ecosystem goods and services, including the production of food (gathering activity) and raw materials (wood harvesting), the regulation of air, water, nutrient cycling, animal populations and disturbances (storm, flood, drought), water supply, soil erosion control, soil formation, pollination, habitat for biodiversity, conservation of genetic resources, as well as recreational and cultural services. Co-benefits are a key reason why some buyers participate in voluntary carbon markets (Hamrick and Gallant, 2017a), and why one offset project may be preferred over another (Goldstein and Ruef, 2016). Co-benefits are covered in REDD+ projects under 'safeguard' mechanisms.

Co-benefits are defined as *additional* economic, environmental and social benefits arising from a carbon project (in addition to what would be the case without the project) based on metrics or indicators defined by the project developer. Co-benefits must take into account unintended negative consequences such as the depletion of groundwater in xeric environments linked to afforestation of certain species. Some carbon offset certification standards allow 'tagging' co-benefits on the carbon credits issued, if they are not already included in the standard (Goldstein and Gonzalez, 2014). This is particularly the case for the co-benefits on local employment and training, the empowerment of women, adaptation to climate change and the protection of biodiversity.

Voluntary buyers of forest carbon offsets increasingly demand the measurement and monitoring of co-benefits. In 2010, there was only one supplementary standard for co-benefits, the Climate, Community and Biodiversity (CCB) standard (Diaz, Hamilton and Johnson, 2011). Other standards have developed over time and include the 'Gold Standard' and 'Plan Vivo' that both measure co-benefits such as ecosystem restoration. In 2016, some 65% of forest carbon projects were certified by a co-benefit standard while co-benefit-certified projects accounted for 78% of the volume of offsets transacted (Hamrick and Gallant, 2017a).

A review of 148 forest carbon project in 2016 shows that all of the projects assessed had at least one type of co-benefit. The most common co-benefits of forest-based carbon offset projects were additional employment and/or training opportunities – 147 projects (98%), followed by community benefits – 75 projects (50%) and then biodiversity – 70 projects (47%). Many projects reported multiple co-benefits; 60% of projects reported at least two, 33% reported at least four, and 8% reported six co-benefits (Hamrick and Gallant, 2017a).

For REDD+ projects, co-benefits become a basic expectation because they can help reduce deforestation, as is the case with the creation of additional employment opportunities, alternative income, community training (Goldstein and Gonzalez, 2014). In response to this demand, the Climate, Community and Biodiversity Alliance (CCBA) facilitated the development of REDD+ Social and Environmental Standards (REDD+ SES) to assess the performance of government-led REDD+ programmes in terms of social and environmental impacts.

2.5. Barriers to scaling up forest carbon offsets

While forest carbon projects have the potential to sequester CO_2 with relatively low operating costs, there are significant barriers to their scaling up globally. For example, the European Union (EU) Emissions Trading System (ETS) and Effort Sharing Decision (ESD) do not include emissions and removals from Land Use, Land Use Change and Forestry (LULUCF) activities under the Kyoto Protocol. This is because the EU is concerned about the accuracy of reporting of emissions and sequestration and because offsets may weaken the incentive to reduce emissions in other sectors (Nabuurs et al., 2015).

Another barrier to the take-up of forest carbon offsets is the complexity associated with carbon accounting. This complexity includes the calculation of the potential carbon stored in different tree species, the carbon stored in different pools, as well as the need to account for the carbon sequestered in the wood after harvest (van der Gaast, Sikkema and Vohrer, 2018). Forest carbon projects must also assess the risk of carbon leakage. The willingness to accept small compensation for preserving a forest in one place might mean that deforestation for cultivation can be done in another place, especially when both places are under the control of a single landowner (Alston, Andersson and Smith, 2013).

The permanence of forest offsets raises concern. Forests are subject to multiple disturbances that include: (i) natural disturbances (such as insects, fires, climatic and natural disasters) and (ii) anthropogenic disturbances (such as logging and forest conversion to other land uses). These impacts are likely to increase with the acceleration of climate change. Permanence issues are addressed by buffer mechanisms and compensation mechanisms such as payments for ecosystem services (PES). Thus, there is a critical need to evaluate the impact on climate change sequestration of current PES schemes and identify PES that can generate greater sequestration per dollar of expenditure (Chu, Grafton and Keenan, 2019).

Natural disturbances are a challenge for forest carbon offsets because of their unpredictability, and also their scale of impact (Galik and Jackson, 2009). For example, in the United States, disturbance by insects and pathogens affects some 20 million ha (Mha) of forest each year (Dale et al., 2001). These disturbances release carbon stored in trees into the atmosphere when affected trees burn or decay (Oliver and Fried, 2013), thereby reducing potential forest carbon offsets. In Australia, forests are affected by wildfires every year and in some years can release large amounts of carbon. For instance, the Australian wildfires in 2019-20 burned more than 7 Mha of temperate forests, resulting in emissions of some 800 $MtCO_2e$ (DISER, 2020).[8] Although fires release significant amounts of CO_2, forests generally recover over time, generating a significant carbon sink in the years following the fire. In most cases where there is no land use change after the fire, the carbon reabsorbed by the regrowth is expected to be equivalent to the carbon lost in the fire. For example, by 2019, 96% of the initial carbon emissions from the 2003 bushfires in the Australian Capital Territory were offset by carbon sequestration from forest recovery (DISER, 2020). A fundamental assumption of IPCC's Managed Land Proxy (MLP) is that the carbon emissions and removals associated with natural effects will average out over space and time; CO_2 emissions from areas affected by natural disturbances should be offset by subsequent removals from the landscape at some point in the future, depending on the ecosystems (IPCC, 2019b).

A challenge for forest carbon projects is their acceptability in international compliance carbon markets such as the Joint Implementation (JI) and the Clean Development Mechanism (CDM) that were initiated, respectively, under Article 6 and Article 12 of the 1997 Kyoto Protocol. The JI created emission reduction credits, emission reduction or emission removal projects while the CDM created saleable certified emission reduction credits (ERCs) from developing countries that could be purchased by developed countries with commitments to reduce their GHG emissions under the Kyoto Protocol. There are, however, significant constraints on the sale of ERCs including complex project document requirements. Consequently, in 2016, only 66 afforestation and reforestation (A&R) projects had been registered by the CDM Executive Board out of 7 715 CDM project registered for all sectors. For the JI, there were three forestry projects out of 604 registered projects. Improved forest management (IFM) and REDD+ are currently outside the scope of JI and CDM (van der Gaast, Sikkema and Vohrer, 2018).

It is important to note that while forests are an important carbon sink for mitigating climate change, the global warming – if not effectively mitigated – may reduce the sequestration capacity of trees and consequently the cost-efficiency of forest-based carbon projects. There is clear scientific evidence that climate change may depress growth rates and shortens the time that carbon resides in the ecosystem by

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[8] By comparison, annual carbon emissions from Australian forest fires were, on average, less than 1.0 $MtCO_2e$/year in the 1990s (Macintosh, 2011).

killing trees under hot, dry conditions (Sullivan et al., 2020). In other words, if global temperatures reach a key threshold, dying trees will release warming gases (Pennisi, 2020). In this case, forest may become less cost-efficient mitigation approach if global warming continues in the future. On the other hand, there are regions where climate change will increase forest productivity (higher atmospheric CO_2 content, higher temperatures and longer growing seasons) or even extend the climatic zones suitable to forests. For example, in Finland, Scots pine and Norway spruce are likely to invade tundra regions under warmer conditions. However, expanding the area or density of forests reduces the Earth’s albedo (i.e. makes Earth’s surface darker), which warms the climate. There is a trade-off between the cooling impact of increased carbon storage and the warming impact of decreasing albedo, especially in the boreal region (Rautiainen, Lintunen and Uusivuori, 2018).

3. Framework for assessing the cost-efficiency of forest carbon sequestration

3.1. Components of forest carbon sequestration costs

The cost of forest-based carbon sequestration can be broadly decomposed into implicit and explicit costs. The implicit cost, or the opportunity cost, is the benefit foregone because economic resources (e.g. land and labour) cannot be used for non-forest income-generating activity (Cacho, Lipper and Moss, 2013). The opportunity cost of land is a significant fraction of the total implicit cost (Moulton and Richards, 1990) of forest carbon sequestration and can range from some USD 120 to 1 400/tC (USD 32–384/tCO_2) depending on the opportunity cost of forested land (van Kooten et al.,2004; van Kooten and Sohngen, 2007). It should be noted that land use is not necessarily changed by forest carbon sequestration. For example, the experience of Emission Reduction Fund participants in Australia shows that rangeland forest ecosystems can be regenerated through management of the timing and extent of grazing activities.

The main incentive to convert forest land for agricultural use is market remuneration for agricultural products, often distorted by agricultural policies. Thus, the first step in improving a country's forest carbon sequestration potential, while removing potentially harmful subsidies for the environment, is to phase out support to agriculture coupled with agricultural production, where applicable. This is all the more important the higher the level of agricultural support. Increasing support for forest activity in order to enhance carbon sequestration would run the risk of repeating in forestry the mistakes that policy reforms are now seeking to address in agriculture (Bonnis, 1995).

The explicit cost of forestry carbon sequestration include the cost of transacting and enforcing the contract between buyers and sellers (Lile, Powell and Toman, 1998), and what is commonly called transaction costs. These costs include: (i) search; (ii) negotiation; (iii) approval; (iv) monitoring; (v) enforcement; and (vi) insurance (Dudek and Wiener, 1996). Milne, 2002 includes three additional transaction costs components: (i) design cost; (ii) implementation cost; and (iii) verification or certification cost. The design cost includes the development of monitoring techniques and verification protocols, methods for baseline and project scenario measurements, and feasibility studies to ensure positive social and environmental benefits result from the project. The implementation cost covers expenses for labour, capacity building, selection of local contracts or sites, community meetings, technical, management plans, legalising leases or registration of land, distribution of funds/subsidy to beneficiaries, distribution of planting material and other inputs. Verification and certification costs are also required to prove to investors that the estimated levels of carbon have been sequestered.

Estimates of transaction costs are highly uncertain because of different accounting practices (Richards and Stokes, 2004), but appear to be a substantial proportion of the overall costs of forest-based sequestration projects (Wittman and Caron, 2009; Wittman, Powell and Corbera, 2015). Pearson et al., 2014 estimate that the transaction costs range from USD 0.09 to 7.71/t CO_2 (USD 0.33–28.3/tC) or from 0.3% to 270% of anticipated income. Pearson et al., 2014 also find that the three largest cost categories are: (1) insurance[9] (under the voluntary market; 41–89% of total costs); (2) monitoring (3–42%); and (3) regulatory approval (8–50%). Milne, 2002 estimates that the transaction costs range from 6% to 45% with absolute values from USD 0.57 to 2.96/tC (USD 0.2 to 0.8/tCO$_2$). This is comparable to estimates by Benítez et al., 2001 who estimate that the transaction costs in forest-based carbon projects in northern Ecuador range from USD 60 to 80/ha for projects with 20-year rotation cycles.

Transaction costs are high in terms of forest carbon offset markets with Hamrick and Gallant, 2017a finding that, of 53 forest carbon offset projects in 2016, most projects only spent 25% of the total revenue from selling carbon offsets on developer staff overhead cost and another 25% on implementation activities. The payment to landowner, local stakeholder and community was roughly between 25%-75%. Some purchasers also pay third parties for verification, issuance and other actions. High transaction costs reduce the gains from economic exchange and the potential size of the market. Thus, approaches to lower the cost of forest carbon projects, such as mitigating the information asymmetry between sellers and the buyer of carbon sequestration services, would promote additional forest carbon sequestration (Peterson et al., 2015).

The following sections propose a framework to compare cost components of forest carbon sequestration and net carbon sequestered between countries. The objective is to prioritise the countries where undertaking forest carbon sequestration projects would be the most cost-efficient.

3.2. A general formula for the cost components of forest carbon sequestration

We adopt the approach proposed by Chu, Grafton and Nguyen, 2021 to calculate the economic cost of forest carbon. The general formula for estimating the average cost of carbon sequestered for each project (e.g. afforestation or forest protection) at time t [AC_t in USD/tCO$_2$e] is provided in Equation (1) where E_0 is the expectation operator at time zero, C_t^{net} is the net cost in dollar term, and Q_t is the net quantity (tCO$_2$e) generated by the project. AC_t can be discounted to time zero using an annual rate ρ such that $AC_0 = \frac{AC_t}{(1+\rho)^t}$.

$$AC_t = \frac{E_0 C_t^{net}}{E_0 Q_t} \qquad (1)$$

The net cost is measured by the production cost (C_t^{prod}) plus the transaction cost (C_t^{tran}) net of any non-carbon benefits that can be generated by forests (B_t^{fore}). The net quantity of carbon is measured by the amount of sequestered carbon when more trees are planted or the amount of avoided emission from tree removal, as the result of the project implementation. The production cost includes the cost of land use, the cost of labour, the cost of materials and capital depreciation, and other cost items. The cost of land use is the expenditure of devoting a specific parcel of land to forest rather than to alternative uses (i.e. opportunity cost). This is a significant part of the production cost because forests are land-intensive (see e.g. Neudert et al., 2018; Sloan et al., 2018). The cost of labour, materials and capital depreciation vary across the objectives of forest projects and countries. Other production costs may include compensation to landowners for the foregone income of selling harvested timber if they choose to keep their forest. The production cost is approximated in Equation (2).

$$C_t^{prod} = C_t^{land} + C_t^{labour} + C_t^{other\ production\ factors} + C_t^{other} \qquad (2)$$

The transaction costs consist of all other cost components, other than the production cost. They comprise the costs of setting up and operating a governance structure to run a project (Marshall, 2013; Nantongo and Vatn, 2019), as well as information, negotiation, regulatory approval and certification, monitoring and verification (M&V) and trading costs (Mundaca et al., 2013). They also include insurance costs (Pearson

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[9] Insurance costs include: (i) project risk insurance; and (ii) costs of insuring the emission reductions.

et al., 2014); with long-term carbon contracts (e.g. 100 years based on US Forest Service permit applications), indemnification of management failures and natural disturbances are necessary for markets to function at national scale.

To derive the average cost of carbon sequestered as per Equation (1), we defined a forest project lifespan of T years. The average cost in the base year (time zero) can be evaluated in equation (3) where $p_t^{tr} \equiv \frac{C_t^{tran}}{C_t^{prod}}$ is the fraction of the transaction cost to the production cost at time t.

$$AC_0 = \frac{\frac{E_0 C_t^{net}}{E_0 Q_t}}{(1+\rho)^t} = \frac{E_0 \sum_{t=0}^{T}\left[\left(\frac{1}{1+\rho}\right)^t C_t^{net}\right]}{E_0 \sum_{t=0}^{T} Q_t} = \frac{E_0 \sum_{t=0}^{T}\left[\left(\frac{1}{1+\rho}\right)^t \left(\left(C_t^{land}+C_t^{labour}+C_t^{material}+C_t^{other}\right)\left(1+p_t^{tr}\right)-B_t^{fore}\right)\right]}{E_0 \sum_{t=0}^{T} Q_t} \quad (3)$$

3.3. Estimating net carbon sequestration

The formula to estimate carbon benefits varies depending on whether it is an afforestation or forest conservation project. In afforestation projects, the carbon benefit is the average amount of extra atmospheric carbon that can be sequestrated via planting and managing trees in non-forest land. The carbon benefit in forest conservation projects is measured by how much, on average, carbon emission can be avoided by conserving and managing forest, taking into account the carbon emission of alternative land use. In both cases, the carbon benefit is estimated by comparing the outcome of the project with an alternative land use.

3.3.1. Afforestation

Net carbon sequestered by an afforestation project (*Q*) in Equation (1) is the amount of carbon sequestered (*CS*) by planting trees *plus* the avoided carbon emission that would have been generated by land use other than forestry (agriculture, grazing, land take for urbanisation) (EM^a), as specified in Equation (4).

$$E_0 \sum_{t=0}^{T} Q_t = E_0(CS|t=T, a=0) \ + \sum_{t=0}^{T-1} EM_t^a \quad (4)$$

In the right-hand side of Equation (4), the first term is the expected amount of carbon sequestration generated by the project. This component is calculated by the expected carbon stock at time T given new trees will be planted (the current age of trees is zero; $a=0$). The second term in the right-hand side of Equation (4) is the *avoided* carbon emissions from alternative land use.

We first consider a 'risk-free' scenario where the trees grow and sequester carbon from the atmosphere and increase carbon stock as specified in Equation (5). In this equation, $CS(a)$ is the carbon stock at age a, $f(a)$ represents the relationship between the tree age and the above-ground biomass (McMahon, Parker and Miller, 2010), D is the fraction of carbon in the total biomas, R is the shoot-to-root parameter – a ratio that helps convert the above-ground biomass to below-ground biomass (Busch et al., 2019), and A is the above-ground biomass at the age of 30 that can be set according to field data.

$$CS(a) = f(a) \times (1+R) \times D \times \frac{A}{f(30)} \quad (5)$$

To account for the likelihood of natural disturbances causing carbon emissions, such as wildfires, we denote the risk at time t as r_t ($t = 0...T-1$). The timing of such events matters because the more advanced the afforestation, the greater the increase in carbon emissions. Using r_t we can estimate the expected carbon stock at time t as per Equations (6-a) and (6-b). Equation (6-a) implies that at the end of the project ($t=T$), the amount of carbon stock is estimated using the age of trees, as described in Equation (5). Equation (6-b) specifies that, at time t, trees could be destroyed with a probability r_t (the first component in the right-hand side) or could continue to grow to a new age with a probability $1-r_t$ (the second component in the right-hand side). Equation (6) is a recursive equation – a special form of the

Bellman equation, and it does not have a closed-form solution. Thus, we use the value function iteration approach to the Bellman equation to have a numerical solution.

$$E_0(CS|t=T,a)=CS(a) \tag{6-a}$$

$$E_0(CS|t,a)=r_t\times\ E_0(CS|t+1,0)+(1-r_t)\times\ E_0(CS|t+1,\mathrm{a}+1) \tag{6-b}$$

3.3.2. Forest conservation

The key difference between forest conservation and afforestation projects is about whether forest trees already exist when a project starts. For afforestation projects, new trees are planted, so their age is assumed to be zero at the beginning of the project. For forest conservation projects, we denote the current age of trees by a_0 where the net carbon benefit can be estimated using Equation (7).

$$Q=E_0\sum_{t=0}^{T}Q_t=[E_0(CS|t=T,a=a_0)-E_0(CS|t=0,a=a_0)]\ \ +[EM+\sum_{t=0}^{T-1}EM_t^a] \tag{7}$$

In the right-hand side of Equation (7), the first bracketed term is the amount of carbon sequestration generated by the project. This component is calculated by the difference between the expected carbon stock at time T and the expected carbon stock at time zero, given the current tree age a_0. The second bracketed term in the right-hand side of Equation (7) is the *avoided* carbon emissions that include a one-off emission (e.g. cutting trees to convert forest to farming, pasture or urban land) and emissions from alternative land use. Assuming the risk of natural disturbances causing carbon emissions at time t as r_t ($t=0\ldots T-1$), the net carbon benefit can be estimated using the formula in Equations (6-a) and (6-b).

3.4. Data sources

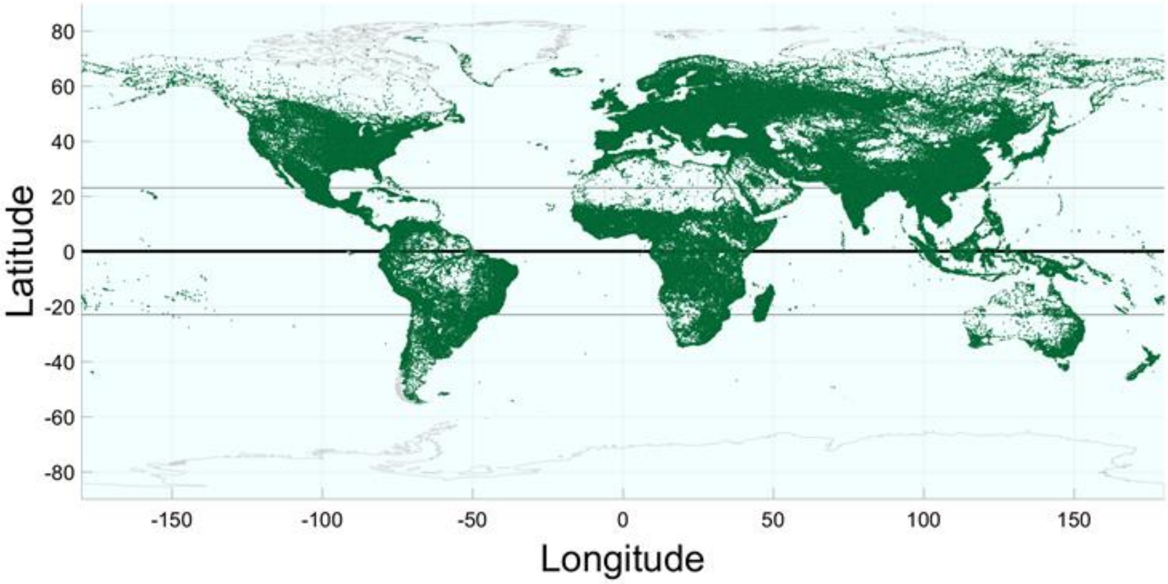
We calibrate the formula for the average cost of forest carbon in Equation (1) by specifying parameter values. We assume the lifespan of the project is 100 years ($T=100$). The discount rate is 4%/year ($\rho=0.04$) – roughly equal to the average rate of 30-year US Treasury bond between 1998 and 2017. The carbon content in the forest biomass is $D=0.47$ (IPCC, 2006). The root-to-shoot ratio is specified to be $R=0.26$ (Busch et al., 2019). The above-ground biomass is approximated by a scale of the square root of age (Busch et al., 2019). The baseline of the average age of existing trees was 60 years in a conservation project.

The alternative land use for forests is dominated by agriculture, both subsistence and commercial (UNFCCC, 2007; FAO and UNEP, 2020). For this reason, the opportunity cost of land use is approximated by the value added of land devoted to agriculture. To take into account the fact that agricultural productivity could vary significantly from one year to another due to weather, we use the average over ten years, from 2008 to 2017. Data of the agricultural value added in USD and agricultural land area are extracted from the World Development Indicators of the World Bank (WDI database). Monetary values are converted to 2017-value USD, using the Consumer Price Index of the United States extracted from the WDI database. The level of GHG emissions for alternative land-use was approximated by the GHG emissions from agricultural activities, which was also extracted from the WDI database.

To approximate the sequestration capacity per ha of land, we use the Normalised Difference Vegetation Index (NDVI) from the Moderate Resolution Imaging Spectroradiometer database of NASA (Didan et al., 2015). National NDVI data is then used to estimate the average carbon stock in each country. Field studies have shown that the mean of NDVI has very high correlations with forest biomass, and this index can be used to predict carbon stock across different climate zones of the world (González-Alonso et al., 2006; Le Maire et al., 2011; Gideon Neba et al., 2014; Bhardwaj et al., 2016; Macedo et al., 2018; Motlagh et al., 2018; Forkuor et al., 2020; Issa et al., 2020). However, the exact mathematical relationship between NDVI and forest quality and age has not been established. Thus, we used the sigmoid function to better relate NVDI to existing forest quality and age and calibrated the sigmoid function based on the global average carbon stock in one hectare of forest land estimated by FAO (FAO, 2020). NDVI data are georeferenced at a 0.05º × 0.05º resolution (i.e. 25.92 million nodes on the Earth surface), and we calculate the NDVI at each resolution node using 246 monthly datasets, from January 2000 to June 2020. At each resolution node, the maximum NDVI value over the 2000-20 period is taken as a proxy for potential sequestration capacity to minimize the impact of changes in NDVI caused by (possibly subsequent) degradation and clearing.

Some countries have sizeable inhabitable regions (e.g. deserts or glaciers) which do not represent the sequestration capacity of forests in their habitable land. To take into account this fact, we use more than 4.09 million sampled habitable places across the global surface to represent liveable places around the world (Figure 4). The average NDVI of each country is approximated using NDVI at habitable places within the country.

Figure 4. Sampled habitable places



Source: Authors.

Labour costs are approximated by the value added per employed person. Data for each country are extracted from the WDI database. Monetary values are converted to 2017-value USD for consistency. When a project involved planting trees, we assumed the cost per hectare was USD 2 000 for material and capital (e.g. depreciation, nursery, tree stacking after plantation if any) plus 1-week labour cost. To account for cost uncertainties, we undertook a sensitivity analysis of how our results respond to different parameters values.

The level of wildfire risk is approximated by historical data extracted from the Global Fire Emissions Database (Randerson et al., 2018). This dataset contains wildfire burning as a fraction of the total area, georeferenced at a 0.25º × 0.25º resolution (i.e. more than 1 million nodes across the Earth surface). To take into account the fact that inhabitable regions are not relevant for forests, we calculated the fire burn fraction around the over 4 million sampled habitable places across the world and estimated the mean of fire burn fraction at each of these liveable places. The wildfire risk for a country is approximated using the average of the burn fraction at all habitable places within the country.

Data for the governance indicator are approximated by the Ease-of-Doing-Business index, extracted from the WDI database. This index is available from 2015 to 2019, and we calculate the average over this period for each country. The average index is used as a proxy for transaction costs. We assume the transaction cost varies with the governance quality, ranging between 10%-90% of the production cost (equivalent to 9%-47% of the total cost), adopting comparable results of Mundaca et al., 2013 and Fichtner, Graehl and Rentz, 2003. In forest conservation, the initial compensation to farmers for not cutting down trees was approximated by forest rent, as extracted from the WDI database.

3.5. Global distribution of cost-efficiency factors

Here, we analyse the global distribution of factors of (i) net costs for forest carbon sequestration (opportunity cost of land, transaction cost, cost of labour) and (ii) net amount of sequestered carbon (forest productivity, avoided agricultural GHGs, wildfire risk) to estimate the cost-efficiency of forest carbon sequestration. For each of the six factors, the 166 countries for which data are available (see Annex C) are classified into four groups, based on their performance. The classification outcome spatially varies from one factor to another (see Figure 5, Figure 6, Figure 7, Figure 8, Figure 9 and Figure 10). It should be noted that such cross-country comparison masks subnational variations that can be significant, especially in large countries. The approach proposed in the document can be applied at any scale provided that reliable data is available on the six factors. Using subnational values for large countries would enhance the policy relevance of the analysis.

Figure 5 shows that the opportunity cost of land for forest-based carbon sequestration is lowest in Russia, Middle Asia, Australia, most of Africa, Mexico, and some parts of South America. Many countries in this group have climate or demographic characteristics unsuitable for intensive agriculture and, thus, the value added per hectare of agricultural land is correspondingly lower.

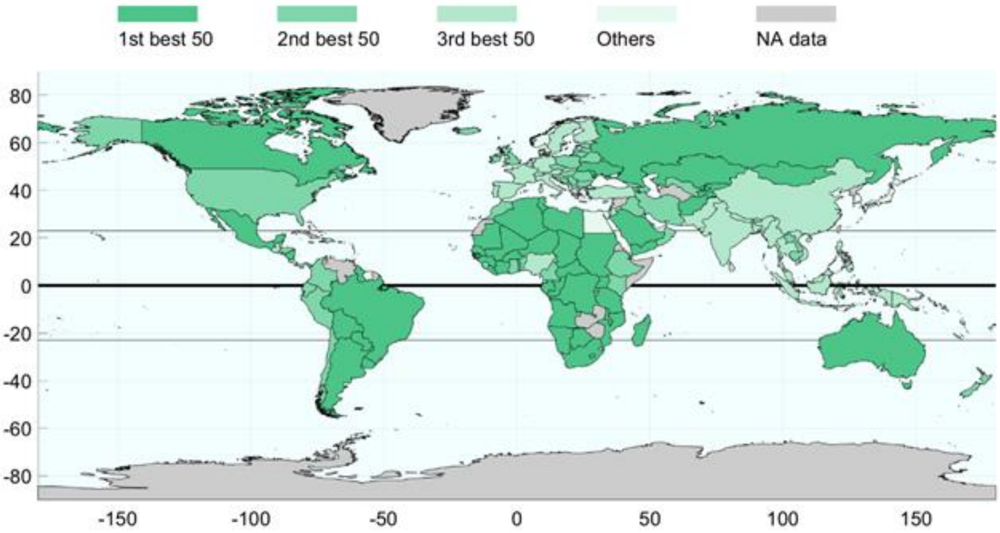
Figure 6 shows the distribution of the mean NDVI index as a proxy for carbon sequestration capacity by forest. The two main regions with the highest rainfall recorded are in South-East Asia and tropical South America. African countries, such as Congo, Cameroon, Liberia, Guinea, Equatorial Guinea, and Sierra Leone also perform well in relation to this cost factor. In terms of developed economies in temperate locations, New Zealand is a low-cost country in this dimension.

Figure 7 shows the level of GHG emissions from agriculture across countries. Sequestration projects in countries that have *higher* GHG emissions from agriculture *avoid* a greater level of carbon emissions, all else equal. The first quartile includes countries with intensive agricultural activities, such as New Zealand, Japan, Korea, India and some countries of the Association of Southeast Asian Nations (ASEAN); Egypt and the Central African Republic in Africa; the Dominican Republic, Suriname, and Chile in Central and South America; and several countries in Northern and Western Europe such as Demark, Finland, Sweden, the United Kingdom, Germany, Poland, France, and Italy. We note that, unlike the other three measures, the GHG emissions per hectare of agricultural land would not be included in the market price of forest carbon offsets in the absence of an explicit or implicit cost on agricultural GHG emissions. Thus, for countries with relatively high agricultural GHG emissions, the market price of forest carbon offsets would not include this external benefit. Consequently, the market price of carbon offsets in countries with high agricultural GHG emissions (in the absence of an implicit or explicit price for agricultural GHG emissions) would be biased, thus indicating a higher carbon sequestration in the market for offsets than the actual carbon sequestration costs from forestry, relative to countries with relatively low GHG agricultural emissions.

The classification in Figure 8 shows the quality of the business environment. Countries that have the most business-friendly environment are mostly in North America, Europe, North Asia, Australia, and New Zealand. Exceptions include Thailand and Malaysia – the two countries in the South East Asia region included in the first quartile of the business environment.

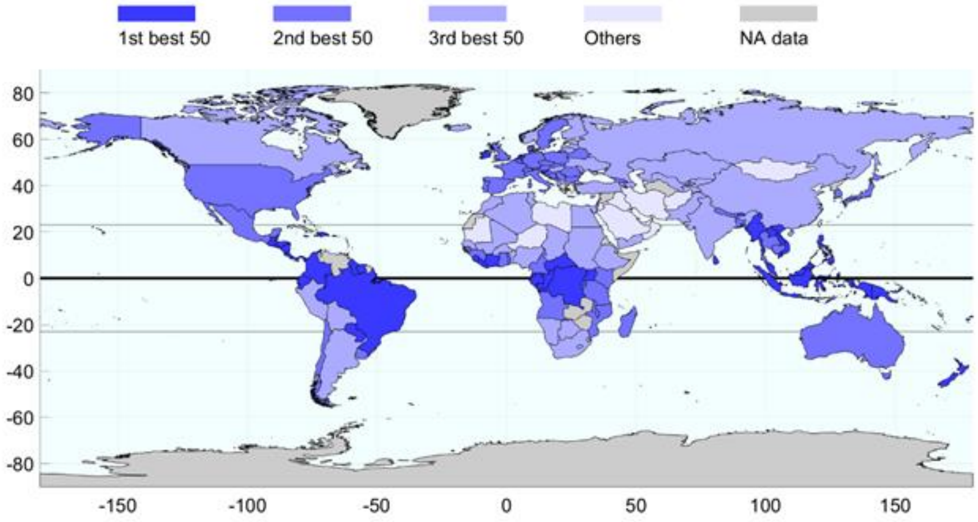
Figure 9 shows the distribution of approximated labour cost, where countries with lower labour costs are considered as the best locations in this criterion. Figure 10 shows the level of wildfire risk across countries. Many countries in Africa have high levels of fire risk. Other countries such as Australia, Brazil, and some South-East Asia countries are also high-risk.

Figure 5. Global distribution of the cost of land use (value added of land used for agriculture)



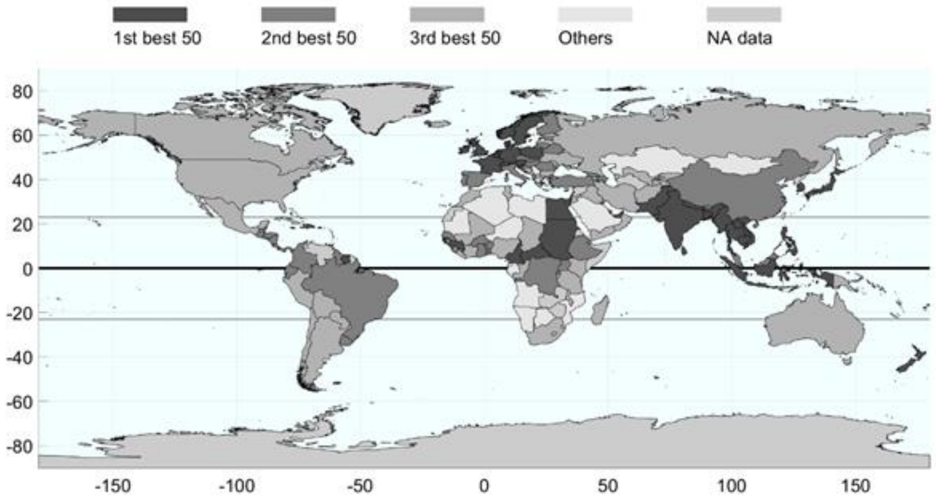
Note: The darker the colour, the lower the opportunity cost of land use for forest.
Source: Authors.

Figure 6. Global distribution of forest productivity (Normalized Difference Vegetation Index)



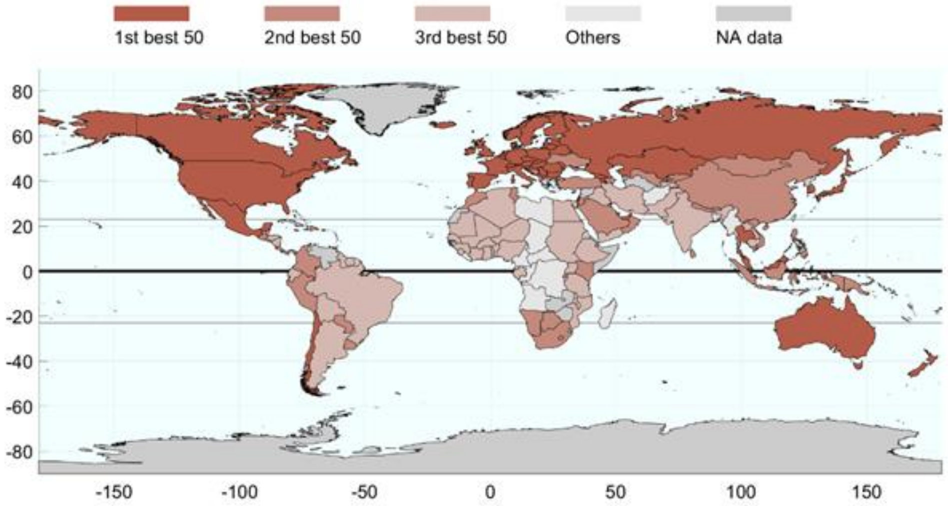
Note: The darker the colour, the higher the forest productivity. The mean NDVI index used to compare countries masks NDVI heterogeneity within the country.
Source: Authors.

Figure 7. Global distribution of GHG emissions from agriculture



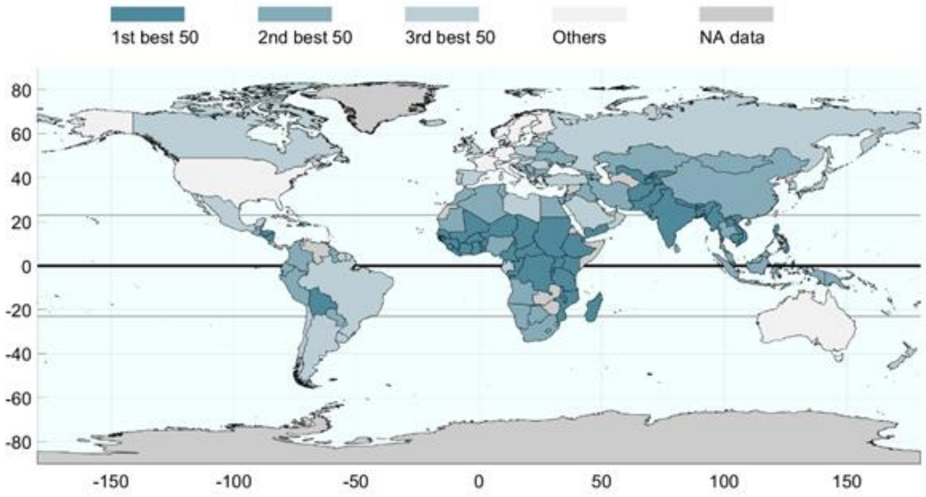
Note: The darker the colour, the higher the GHG emissions from agriculture (the more afforestation can prevent them).
Source: Authors.

Figure 8. Global distribution of transaction costs (Ease-of-Doing-Business index)



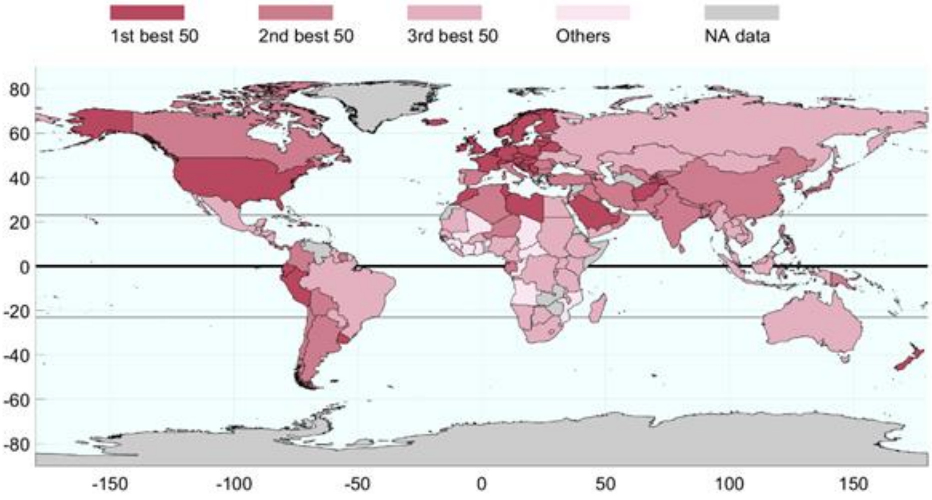
Note: The darker the colour, the lower the transaction costs.
Source: Authors.

Figure 9. Global distribution of labour costs



Note: The darker the colour, the lower the labour costs. Labour cost is approximated by the economy's value added per employed person.
Source: Authors.

Figure 10. Global distribution of wildfire risk



Note: The darker the colour, the lower the wildfire risk. The national wildfire risk average used to compare countries masks the heterogeneity of wildfire risk within the country.
Source: Authors.

3.6. Correlations between cost-efficiency factors

Ideally, forest-carbon projects would be most cost-efficient in a country that belongs to the first group of all six factors. We observe, however, that no country is included in the best group for all six cost-efficiency factors. The correlations between factors must be taken into account to identify the countries where the sequestration of forest carbon is, all factors considered, the most cost-efficient.

To compare them, the factor data is first converted into indices from zero to 1, zero corresponding to the lowest production/transaction cost values and the highest net sequestration values. The indices are then used to calculate the statistical correlation between each pair of factors. The correlation ratios, between -1 and 1 by construction, show the level and the direction of the correlation. A negative correlation indicates a weakening relationship while a positive correlation implies a reinforcing relationship. No statistical significance test was performed in the absence of statistical distributions for normalised indexes such as NDVI (the forest productivity proxy) and ease of doing business (the proxy for transaction cost).

Table 6 shows that of the 15 pairs of factors, two have significant correlations (greater than 0.5). The opportunity cost of land use has a negative correlation with agricultural GHG emissions. This implies that countries with a low opportunity cost of land use are more likely to have a high level of (potentially avoided) GHG emissions from agriculture. Another observation is that the global distribution of labour costs (Figure 9) is close to the opposite of that of transaction costs (Figure 8), suggesting that the quality of business environment is strongly correlated with labour costs (i.e. with the qualification of the labour force).

Table 6. Correlations between cost-efficiency factors (in index form)

	Opportunity cost of land-use	Forest productivity	Agricultural GHG emissions	Transaction costs	Labour costs	Wildfire risk
Opportunity cost of land-use		-0.10	-0.92	-0.19	0.17	-0.09
Forest productivity			0.16	0.06	-0.04	-0.07
Agricultural GHG emissions				0.12	-0.18	-0.01
Transaction costs					-0.59	0.49
Labour costs						-0.32
Wildfire risk						

Note:
Negative correlation indices between -1 and 0, zero corresponding to the lowest correlation value and -1 to the highest correlation value.
Positive correlation indices between 0 and +1, zero corresponding to the lowest correlation value and +1 to the highest correlation value.
Source: Authors.

4. Assessment of countries where forest carbon sequestration would be the most cost-efficient

In this section, we estimate the average cost-efficiency of forest carbon sequestration in each country by combining the six factors presented in section 3.5 with the co-benefits generated by forestry projects. The ranking of countries is based on the individual rankings for the six factors and forest co-benefits. We distinguish between private co-benefits (income from the sale of harvested timber) and non-private co-benefits (the monetary value of ecosystem services other than carbon sequestration). We draw from the estimates of the global values of forest co-benefits by Costanza et al., 1997 and Costanza et al., 2014. In particular, the estimated values of ecosystem goods and services generated by forests globally are, on average, USD 1 338/ha and USD 3 800/ha in 1997 and 2011 (2007-dollar value). Apart from climate regulation (regulation of global temperature, precipitation, and other biologically mediated climatic processes at global or local levels), these goods and services include: food production (by hunting, gathering, subsistence farming or fishing), production of raw materials (lumber, fuel or fodder), air regulation, disturbance regulation (storm protection, flood control, drought recovery), water regulation, water supply, soil erosion control, soil formation, nutrient cycling regulation, pollination, regulation of animal populations, habitat for biodiversity, conservation of genetic resources, recreation, and cultural services (aesthetic, artistic, educational, spiritual, and/or scientific services).

We exclude climate regulation (which covers carbon sequestration) and the production of food and raw materials (which are private co-benefits) and consider the rest of the ecosystem goods and services listed by Costanza et al. – USD 893/ha and USD 2 667/ha in 1997 and 2011 (2007-dollar value) – as non-private co-benefits. To differentiate the non-private co-benefits by country, we adjust the global average value of Costanza et al. with the forest productivity of each country as estimated by the NDVI (see section 3.5). Likewise, the global average value of private co-benefits estimated by Costanza et al. – USD 250/ha and USD 422/ha in 1997 and 2011 (2007-dollar value) for the production of food and raw materials – is adjusted by country using the opportunity cost of land use as estimated by the value added of land used for agriculture.

The cost-efficiency of forest carbon sequestration is estimated with and without non-private co-benefits. When only private co-benefits are accounted for, we call it economically viable cost of forest carbon (i.e. the financial gap per tonne of carbon sequestered between the costs of forest carbon management and income from the sale of wood). When non-private co-benefits are included, the result will reflect the cost-efficiency of forest carbon sequestration from a society's perspective. In both cases, we use the 1997 estimate from Costanza et al. for our low-value scenario and the 2011 estimate for our high-value scenario. Their average is our medium-value scenario. All monetary values are converted to a 2017 value for consistency.

4.1. Economically viable cost of forest carbon

Economic viability is key in deciding whether or not to participate in a forest carbon project. Economic viability is ensured when the income from timber exceeds the private cost incurred in the implementation of the project. If this is not the case, sufficient financial compensation (remuneration for the sequestration service) must be considered to make the project viable and attractive.

4.1.1. Baseline scenario

The baseline results of economically viable costs are summarised in Table 7. In this table, we report the global average, taking away 10% outliers. These outliers are small countries with expensive land use cost, so they are not relevant for land-intensive industries like forests. For example, Maldives is the country with the lowest cost-efficiency if afforestation projects were implemented there: the land use cost is USD 24 500/ha/year – about 40 times the world average. Another outlier is Singapore, where the opportunity cost of land use is USD 145 000/ha/year, nearly 250 times the world average.

Table 7. The cost-efficiency of forest carbon projects with private co-benefits (USD/tCO_2 -2017 values)

Value of private co-benefits[1]	Project category	Global average -10% outliers excluded[2]	100 best countries	50 best countries
Low	Afforestation	57 [12-169]	36	25
	Forest conservation	24 [3-74]	15	9
Medium	Afforestation	47 [11-145]	29	21
	Forest conservation	19 [3-57]	11	7
High	Afforestation	34 [9-108]	21	16
	Forest conservation	13 [2-46]	8	4

Notes:
1. Baseline values of USD 250/ha (low), USD 336/ha (medium) and USD 422/ha (high) – after Costanza et al. – adjusted to the value added of land used for agriculture in each country.
2. Inside the square brackets is the range.
Source: Authors.

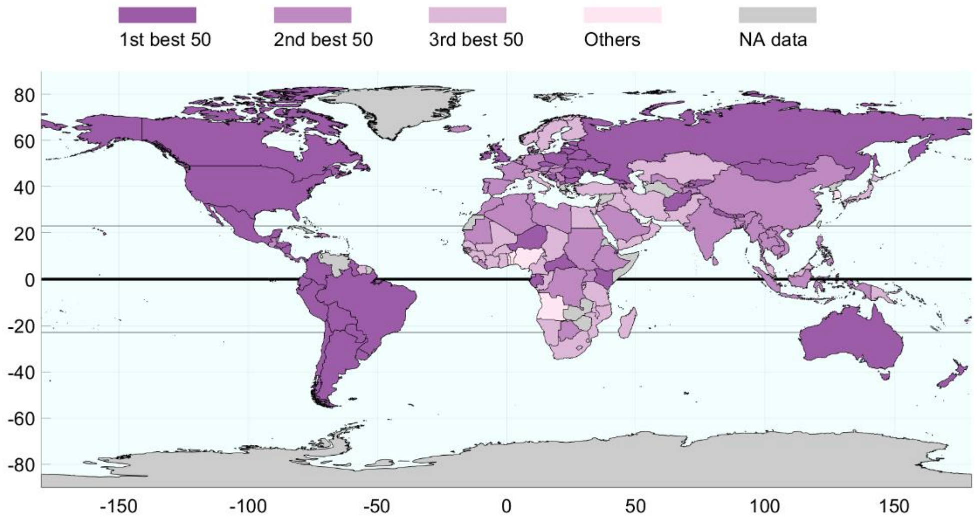
Table 7 shows that the global average cost-efficiency of forest carbon sequestration varies according to the private co-benefits of the forest carbon project (i.e. depending on the level of income from the sale of timber) and whether it is an afforestation or forest conservation project. The global average carbon cost through afforestation projects is estimated to be between USD 34-57/tCO_2, depending on the co-benefits from the sale of timber. At the country level the range is USD 12-169/tCO_2 in the low co-benefits scenario and USD 9-108/tCO_2 in the high co-benefits scenario.

For forest conservation projects, the estimated global average cost of carbon credits varies between USD 13-24/tCO_2, less than for afforestation projects. There are two main reasons for this. First, forest conservation helps avoid CO_2 emissions from deforestation, a GHG impact generally much greater than agricultural GHG emissions avoided by afforestation projects (as per formulas for calculating net carbon sequestered by afforestation and forest conservation in section 3.3). Second, afforestation involves a substantial cost of labour and material during the planting phase.

Table 7 shows that the average cost of forest carbon varies when projects are targeted to different groups of countries. In particular, the average cost of sequestration by afforestation in the top 100 countries is around USD 21-36/tCO_2, or approximately 40% lower than the global average. The average cost through forest conservation in the best 100 countries is about USD 8-15/tCO_2, also about 40% lower than the global average. Targeting forest projects to the best 50 countries would further reduce the costs of forest carbon sequestration.

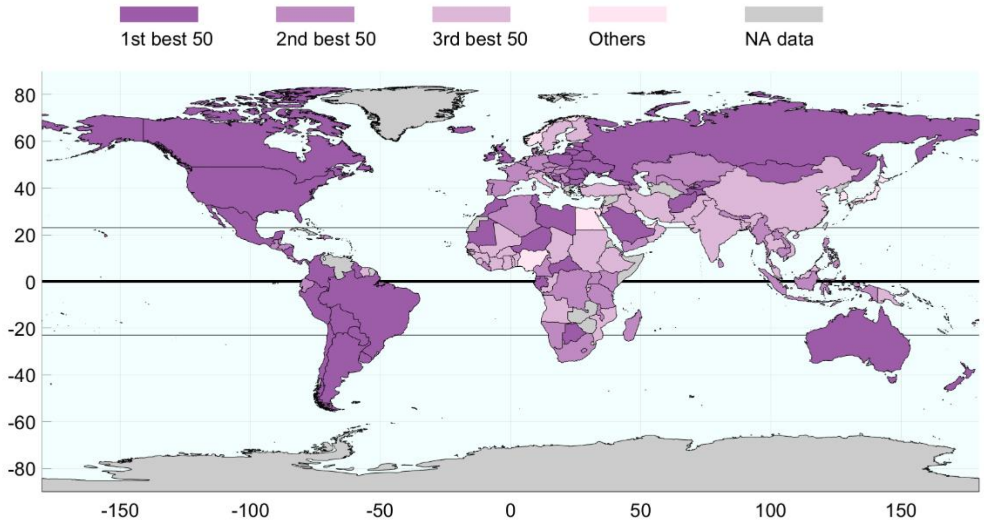
We plotted a global distribution of the economically viable cost of forest carbon in Figure 11 and Figure 12 using the average of the low, medium, and high values of private co-benefits. The figures show that forest carbon projects are likely to be more cost-efficient in some countries and regions than in others. In particular, a few African countries, a few Asian countries, many Latin American countries, North America countries, Oceania countries, EECCA (Eastern Europe, Caucasus and Central Asia) countries, Baltic countries, countries of the east of Europe, Ireland and the United Kingdom appear to be cost-efficient places to sequester forest carbon through both afforestation and forest conservation. Cost-efficiency differs between countries in Europe, Africa and Asia, although it should be noted that despite climatic conditions conducive to high forest productivity, Southeast Asian countries are not among the most cost-efficient countries to sequester forest carbon due to the high cost of land use and the relatively low quality of the business environment.

Figure 11. Global distribution of the economically viable cost of carbon sequestered through afforestation



Note: The darker the colour, the more cost-efficient carbon sequestration by afforestation with private co-benefits.
Source: Authors.

Figure 12. Global distribution of the economically viable cost of carbon sequestered through forest conservation



Note: The darker the colour, the more cost-efficient carbon sequestration by forest conservation with private co-benefits.
Source: Authors.

4.1.2. Sensitivity analysis

There are four parameters that might possibly influence the results where we are not able to find reliable and meaningful proxy data for all 166 countries. These parameters are: (i) the average cost of capital and material in planting activities, e.g. depreciation, nursery, tree stacking after plantation - if any, (ii) the average labour time required in planning activities, (iii) the average lifespan of a project, (iv) the average age of existing trees in a conservation project. Thus, we undertook a sensitivity analysis to examine how our results respond to these parameters.

The sensitivity analysis was undertaken by varying each of these parameters in a range to control for possible uncertainties in their values. In particular, we varied the average cost of capital and material between USD 1 000/ha and USD 3 000/ha, noting that the baseline value was USD 2 000/ha. The labour time required in planning activities was varied between 0.5 and 1.5 weeks per ha with the baseline value given at a week per ha. The average project lifespan was varied between 50 and 100 years with the baseline value set at 70 years. The baseline of the average age of existing trees was 60 years in a conservation project, and we varied this parameter in the range [30–90].

The sensitivity analyses are summarised in Table 8. This table includes results for the baseline parameter values and the results with the minimum and maximum parameter values in brackets. In all cases, the proportional change in the results is relatively small compared to the corresponding change in the parameter values. For example, when the capital and material cost was varied within 50% of the baseline value, the average cost of carbon benefits changed by only 10-15%.

Table 8. Sensitivity analysis (USD/tCO_2 -2017 values)

Value of private co-benefits	Project category	Time horizon (years): 70 [50 - 100]	Age of trees (years): 60 [30-90]	Material cost (USD'000): 2 [1 - 3]	Labour time/ha (week): 1 (0.5-1.5)
Low	Afforestation	57 [50 - 62]	57 [57 - 57]	57 [48 - 65]	57 [56 - 58]
	Forest conservation	24 [23 - 24]	24 [24 - 25]	24 [22 - 26]	24 [24 - 25]
Medium	Afforestation	47 [41 - 51]	47 [47 - 47]	47 [38 - 54]	47 [46 - 48]
	Forest conservation	19 [18 - 19]	19 [19 - 20]	19 [17 - 21]	19 [19 - 19]
High	Afforestation	34 [29 - 38]	34 [34 - 34]	34 [27 - 40]	34 [33 - 35]
	Forest conservation	13 [13 - 13]	13 [13 - 13]	13 [11 - 15]	13 [13 - 13]

Note: Outside brackets are the results for baseline parameter values of the global average; inside brackets are corresponding results for minimum and maximum parameter values.
Source: Authors.

4.2. Incorporating non-private co-benefits

When estimating the cost-efficiency of forest carbon sequestration from a society's perspective, we consider three categories of forestry projects, afforestation, reforestation and forest conservation, due to a possible difference in non-private co-benefits. Afforestation is the conversion of other land uses to forests, whereas reforestation is the restoration of degraded forests or deforested lands to forest. For this reason, we assumed that reforestation could potentially restore all co-benefits of the original forests, if the project is long enough, while afforestation can only generate a fraction (assuming afforestation takes place on originally wooded land). This fraction was specified at 15%, 37%, and 58% for the low, medium, and high values of non-private co-benefits respectively, corresponding to the ratio between normal and high-quality forests, approximated as the ratio between the co-benefits of temperate/boreal forests and tropical forests (Costanza et al., 1997; Costanza et al., 2014). This is a conservative estimate. Newbold et al., 2015 estimate that, compared to primary vegetation, intensive plantation forest retains 61% of species richness, 96% of total abundance and 57% of rarefaction-based richness.

Table 9 shows that the global average cost-efficiency of forest carbon sequestration varies according to the non-private co-benefits of the forest carbon project (i.e. depending on the level of air, soil, water, biodiversity and cultural services provided by the forest) and whether it is an afforestation, reforestation or forest conservation project. As with the economically viable cost of forest carbon and for the same reasons, the estimated global average cost of carbon credits is lower in forest conservation projects than in afforestation projects, with reforestation projects in between. A major difference, however, is that taking into account non-private (environmental and social) co-benefits significantly improves the cost-efficiency of forest carbon projects compared to considering the sole private (wood) co-benefits. Taking into account non-private co-benefits, the range of the global average dollar cost for a ton of CO_2 is [0, 54] for afforestation, [-28, 36] for reforestation, and [-53, 2] for forest conservation. These numbers are much lower than the results in Table 7, where only private co-benefits are considered.

Table 9. The cost-efficiency of forest carbon projects with non-private co-benefits (USD/tCO$_2$ -2017 values)

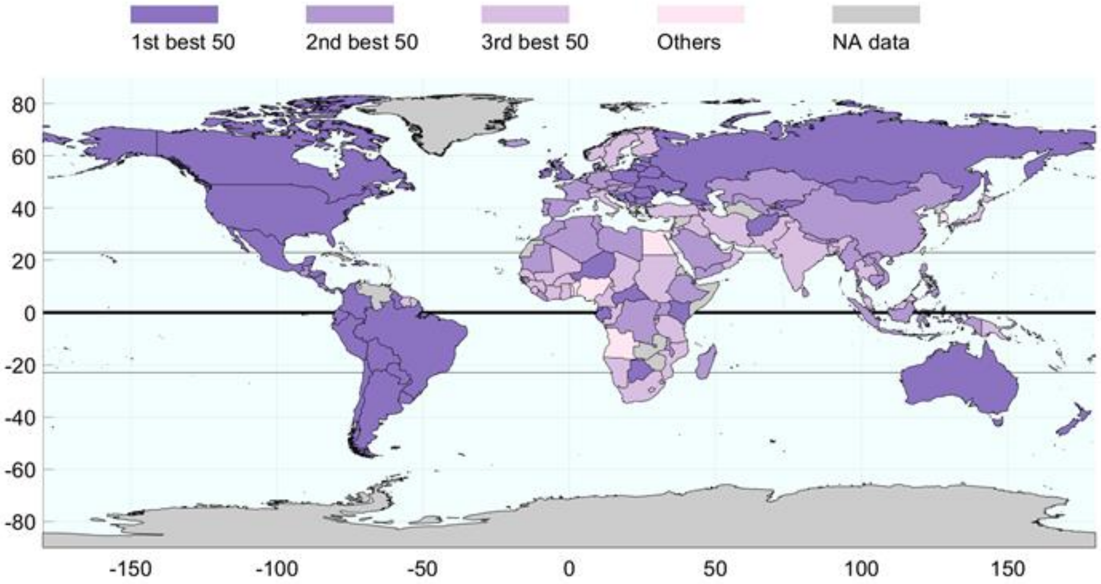
Value of non-private co-benefits[1]	Project category	Global average (10% outliers excluded)[2]	100 best countries	50 best countries
Low	Afforestation	54 [10-166]	33	22
	Reforestation	36 [-11-148]	15	3
	Forest conservation	2 [-23-56]	-9	-15
Medium	Afforestation	33 [-4-133]	15	7
	Reforestation	6 [-36-117]	-12	-21
	Forest conservation	-23 [-48-28]	-34	-40
High	Afforestation	0 [-31-73]	-14	-20
	Reforestation	-28 [-65-52]	-42	-50
	Forest conservation	-53 [-77-1]	-63	-68

Notes:
1. Baseline values of USD 893/ha (low), USD 1 780/ha (medium) and USD 2 667/ha (high) – after Costanza et al. – adjusted to the Normalised Difference Vegetation Index (NDVI) in each country.
2. Inside the brackets is the range.
Source: Authors.

Further, the global average cost of forest carbon can turn negative when non-private co-benefits are taken into account. A negative value implies that the non-private co-benefits exceed the production and transaction costs of implementing the forest carbon project. In other words, if a forest carbon project has a negative cost, it can both sequester carbon cost-efficiently and provide ecological and social services. The much lower cost of carbon credits with non-private co-benefits emphasises the role of climate policy in promoting biodiversity and other public benefits related to forests.

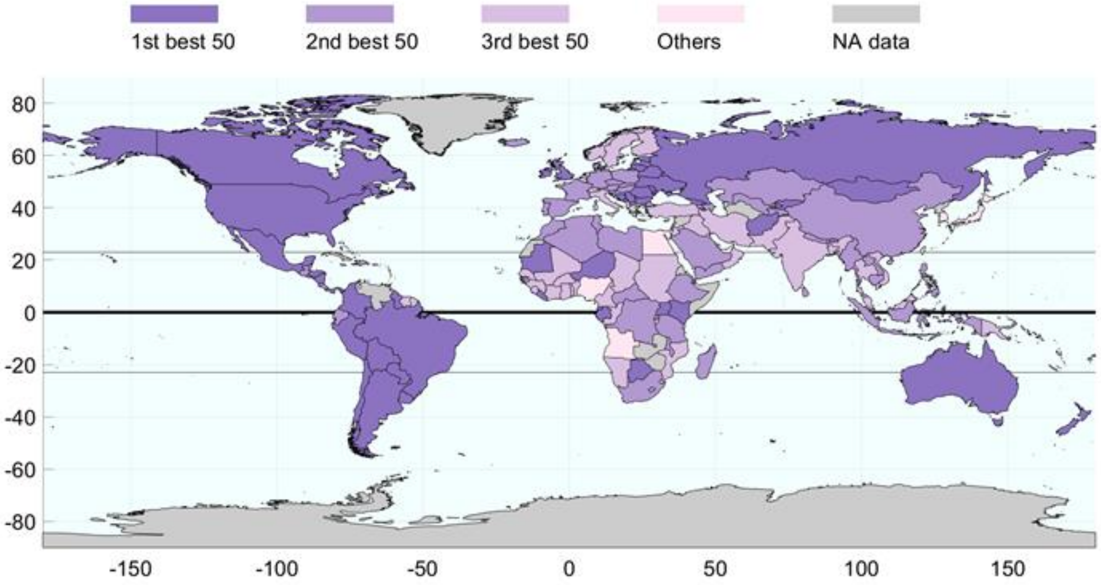
Interestingly, the global distribution of cost-efficiency of carbon sequestration with non-private co-benefits strongly resembles that with private co-benefits (i.e. that with the economically viable cost of forest carbon). Figure 13, Figure 14 and Figure 15 show the global distribution for the three categories of forest project with non-private co-benefits; for afforestation and forest conservation, the global distribution is very similar, but not identical, to that of economically viable cost of carbon in Figure 11 and Figure 12. The ranking of some countries varies slightly within the best groups (top 50, top 100, top 150) but the composition of the groups remain more or less the same. With minor variations, whether through afforestation or forest conservation, the 50 countries where carbon sequestration is the most cost-efficient are basically the same. The selection of countries in which to sequester forest carbon therefore depends little on the benefits associated with the preservation of the local economy (wood production) or on environmental and social values.

Figure 13. Global distribution of cost-efficiency with non-private co-benefits for afforestation



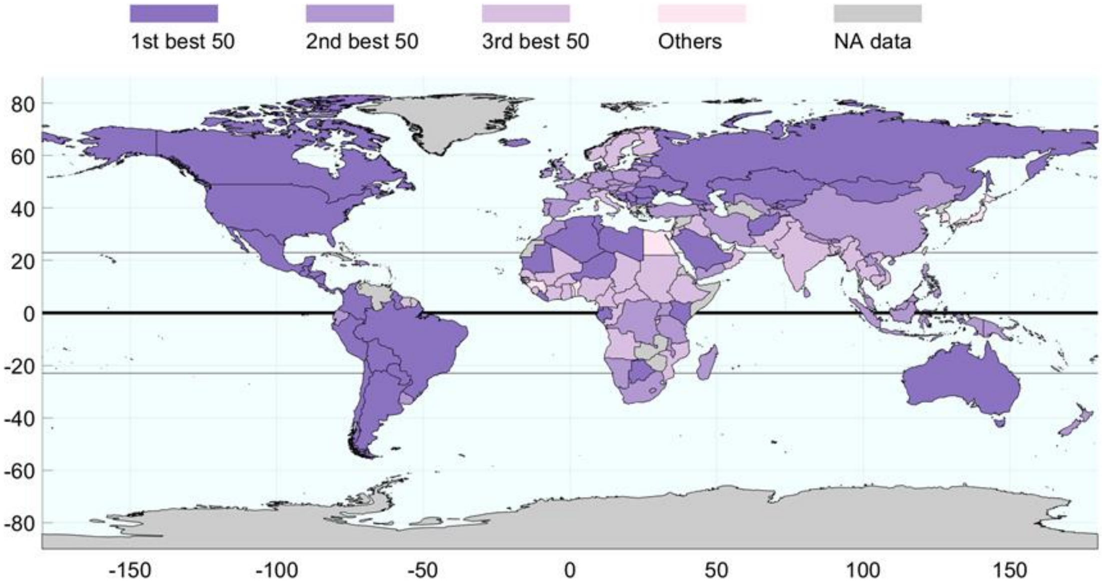
Note: The darker the colour, the more cost-efficient carbon sequestration by afforestation with non-private co-benefits.
Source: Authors.

Figure 14. Global distribution of cost-efficiency with non-private co-benefits for reforestation



Note: The darker the colour, the more cost-efficient carbon sequestration by reforestation with non-private co-benefits.
Source: Authors.

Figure 15. Global distribution of cost-efficiency with non-private co-benefits for forest conservation



Note: The darker the colour, the more cost-efficient carbon sequestration by forest conservation with non-private co-benefits.
Source: Authors.

Twelve (out of 38) OECD countries are in the top 50: Australia, Canada, Chile, Colombia, Estonia, Ireland, Latvia, Lithuania, Mexico, New Zealand, United Kingdom and United States (Table 10). The ease of doing business is the main reason, followed by the low risk of wildfire (for the three Baltic States, Ireland, New Zealand, the United Kingdom, and the United States), the low opportunity cost of land (Australia, Canada, Mexico) and agricultural emissions avoided (Ireland, New Zealand, United Kingdom).

Only Brazil and Russia (out of the 6 BRIICS) are in the top 50 (Table 10) thanks to the low opportunity cost of land and, for Brazil, also because of high forest productivity. China is not in the top 50 for any of the 6 factors of cost and quantity of forest carbon sequestration. The other three BRIICS are not in the top 38 despite high forest productivity in Indonesia, low labour cost in India, low opportunity cost of land in South Africa and avoided agricultural emissions (India, Indonesia).

Four of the 5 most forested countries - Brazil, Canada, Russia and the United States - are in the top 50; only China is not included (Table 10). The top 38 have at least a top 50 in the six factors of cost and quantity of forest carbon sequestration presented in section 3.5; half have two, four have three and two are top 50 in four factors (Ireland and New Zealand).

Table 10. Countries where forest carbon sequestration is most cost-efficient

Country	Afforestation		Forest conservation	
	Economically viable[1]	With non-private co-benefits[2]	Economically viable[1]	With non-private co-benefits[2]
AFRICA				
Gabon	3	1	1	3
Niger	28	27	19	17
Sao Tome and Principe	24	23	34	29
ASIA				
Mongolia	36	25	3	1

Bhutan	5	5	11	22
Afghanistan	49	47	12	25
LATIN AMERICA				
Bolivia	8	3	2	5
Guyana	6	2	8	6
Paraguay	35	14	29	7
Argentina	22	24	14	13
Colombia	7	6	10	14
Nicaragua	20	12	32	15
Mexico	47	35	40	16
Brazil	14	10	15	21
Panama	11	7	18	23
Uruguay	1	4	4	28
Chile	38	37	41	35
Peru	32	34	35	40
NORTH AMERICA				
United States	18	22	13	27
Canada	33	33	23	31
OCEANIA				
Australia	39	21	9	2
Fiji	27	29	42	33
Vanuatu	12	11	31	38
New Zealand	10	19	27	-
EUROPE				
Bulgaria	19	16	28	24
Bosnia-Herzegovina	17	13	25	30
Latvia	16	17	21	36
Lithuania	13	15	17	39
Romania	37	39	43	45
Ireland	4	9	6	-
Estonia	26	32	36	-
United Kingdom	25	38	38	-
EECCA (Eastern Europe, Caucasus and Central Asia)				
Kyrgyz Republic	21	18	7	8
Russia	31	28	24	9
Ukraine	41	31	33	11
Moldova	23	26	30	20
Georgia	9	8	16	34
Belarus	15	20	26	49

Note: Countries in the top 50 for all (or at least three) columns in the table; grouped by geographic area and, within each geographic area, ranked in decreasing order of cost-efficiency of carbon sequestration through forest conservation, taking into account all co-benefits (last column on the right); - . not ranked in the top 50.
1. Considers the private co-benefits of carbon sequestration (wood harvesting)
2. Takes into account the non-private co-benefits provided by the forest (protection of air, water, biodiversity, cultural services)
Source: Authors.

Annex A. Voluntary Carbon Markets

The voluntary offset market is dominated by a handful of private firms that certify offsets using methodologies they have developed themselves. In general, these firms follow the standard criteria (see Box A2.1), but many of them add requirements to differentiate their products from those of their peers.

The Australian Emissions Reduction Fund is one of the few examples of government-led voluntary offset programmes. The Fund focuses on the domestic development of offset projects and is unique in its approach in that it allows a variety of forest carbon offsets into its auctions.

A point of difference exists between different offset standards in terms of the ex-post or ex-ante issuance of verified credits. Those who issue credits on an ex-post basis (e.g. American Carbon Registry) argue that it is necessary to wait for verification of real measured sequestration in biomass relative to baseline. Given the lag times for this verification to occur in forest carbon projects, some standards organisations (e.g. Plan Vivo Foundation) have argued for ex-ante sale of credits to fund the projects. This requires both a modelled baseline and modelled outcomes from adoption of an offset project plan.

Verified Carbon Standard

The Verified Carbon Standard (VCS)[10] is currently the largest certifier of voluntary offsets. The organisation that oversees the standard was first established in Switzerland in 2007. It is administered by Verra, a US not-for-profit organisation[11] founded in 2005 for the purpose of establishing independent quality assurance in voluntary carbon markets. Verra manages five payment for ecosystem services-related programmes:

- VCS, which is Verra's flagship programme solely focused on carbon pricing for voluntary GHG reduction credit trading
- VCS Jurisdictional and Nested REDD+ Framework (JNR) that provides guidance to governments to support forest conservation and enhancement projects that can fit under the REDD+ framework as a part of the VCS programme
- Climate, Community, and Biodiversity (CCB) programme that is a certified standard for carbon credits with a focus on guaranteeing projects also to improve livelihoods, create employment, protect traditional cultures, and protect endangered species
- Sustainable Development Verified Impact Standard (SD VISta) that provides a flexible framework for assessing Sustainable Development Goals' contributions of project-based activities
- Verra California Offset Project Registry (OPR) is approved by CARB to administer certified carbon credits for use in California's mandatory cap-and-trade system.

VCS has the greatest variety of methodologies for forest carbon projects of any of the private sector entities. Unlike some of the other standards, VCS does not focus on A/R[12] .

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[10] VCS originally stood for Voluntary Carbon Standard.

[11] Registered 501(c)(3).

[12] VCS also uses the REDD + category.

Climate, Community and Biodiversity

Climate, Community, and Biodiversity (CCB) standards identify projects that simultaneously address climate change, support local communities and smallholders, and conserve biodiversity. Managed by Verra, CCB standards were developed through a multi-stakeholder process by the CCB Alliance – an NGO partnership including Cooperative for Assistance and Relief Everywhere (CARE), Conservation International, The Nature Conservancy, the Rainforest Alliance, and the Wildlife Conservation Society.

CCB was developed because carbon projects have a potential to restrict the access of Indigenous peoples and local communities to lands on which they have traditionally relied. CCB projects are designed to create employment, improve livelihoods, protect traditional cultures, and protect endangered species while also delivering lower carbon emissions relative to business as usual. CCB standards can be applied to any existing land management project, including projects certified under the VCS programme.

American Carbon Registry

The American Carbon Registry (ACR) was founded in 1996 by the NGO Environmental Defense Fund (EDF) and was initially implemented by EDF's Environmental Resources Trust. Initial funding came from philanthropic contributions and fee-for-service revenues. ACR is an approved Offset Project Registry (OPR) for the California cap-and-trade system.

ACR does not confine its projects to the United States and works globally. There is an emphasis on projects that increase economic opportunities, sustain natural resources, and address differences in opportunity for disadvantaged communities.

ACR registers forestry offset projects from the following project categories:

- A/R: only applicable in non-REDD countries on degraded land that should not have surface disturbance greater than 10% in the process of implementing the offset project plan
- IFM: IFM plans require that privately held forested land be managed commercially for timber harvest, the baseline being management that maximises the economic profitability of the forest
- REDD+

All ACR project audits are done ex-post. ACR's definition of *real offset* requires that the result of an action yields quantifiable and verifiable GHG reductions and/or removals after-the-fact.

Gold Standard

The Gold Standard (GS) was created by the World Wildlife Fund (WWF) and other NGOs in the early 2000s. It now has more than 1 400 certified projects in 80 countries. GS emphasises delivering co-benefits; in 2017 a new standard called Gold Standard for Global Goals (GS4GG) was launched that focuses on co-benefits that are defined by the UN Sustainable Development Goals (SDGs).

The GS4GG programmes require that emissions are not only reduced or sequestered in a real and measurable way that meets the additionality requirement, but they must also meet at least two of the SDGs. In addition, any GS4GG certified project must adhere to "safeguarding principles and requirements" that apply to human rights, gender equality and women's rights, community health, safety and working conditions, cultural heritage, indigenous peoples, displacement and resettlement, corruption, impacts on water resources, landscape modification, use of genetically modified organisms, critical habitat, and endangered species.

The GS focuses on A/R projects. In order to qualify for A/R credits the project area must not have been harvested in the prior 10 years. The project should not take place in a wetland. Like many other A/R methodologies less than 10% of the project area can be subjected to soil disturbance. There can be no irrigation except for what is used in planting.

Plan Vivo

The Plan Vivo Foundation is a registered Scotland charity, based in Edinburgh, which started with a pilot project in Chiapas, Mexico in 1994 and has grown to more than 31 projects in the pipeline. Plan Vivo (PV) projects put emphasis on the flow of value from offsets to the hosts of the offset projects. Projects selling PV credits are required to aim to deliver at least 60% of the proceeds of sales to communities.

The Plan Vivo standard supports rural smallholders and community groups anywhere in the world with a view to generating livelihood, climate, and ecosystem benefits. Communities take a leading role in developing their ‘plan vivo’ to manage their land according to their needs and priorities. The plan vivo is the basis for a PES agreement with a project coordinator and must include a benefit sharing mechanism. PES agreements are established based on the principle of Free, Prior, and Informed consent (FPIC), as stated in the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP).

Plan Vivo adopts a unique approach to project crediting in that it allows for both ex-post and ex-ante issuance of verified credits. In 2016-17, Plan Vivo issued 0.5 million tCO_2e of offsets, which were transacted at an average price of USD 8/tCO_2e.

Climate Action Reserve

The Climate Action Reserve (CAR) was founded in 2008. It is focused on the US carbon markets and the development of domestic projects. CAR was approved by the California Air Resources Board (CARB) as an Offset Project Registry (OPR) under the California cap-and-trade system. Offsets issued by the CAR are not directly eligible for use in the cap-and-trade system but may become so over time. CAR is the third largest contributor of offsets within the California cap-and-trade system.

Emissions Reduction Fund

The Carbon Credits (Carbon Farming Initiative) Act of 2011 aims to remove GHGs from the atmosphere and avoid GHG emissions in order to meet Australia’s climate policy goals. The Emissions Reduction Fund (ERF) was established under the Act in 2015 to encourage low-cost GHG mitigation through domestic projects. The Australian government initially allocated AUD 2.55 billion (USD 2.3 billion) to the Fund. An additional AUD 2 billion (USD 1.4 billion) was provided in 2019 to build on ERF and continue investment in low cost abatement. Under the ERF, eligible projects -- associated with vegetation management, agriculture, energy consumption, waste, transport, coal and gas production or industrial processes -- earn Australian Carbon Credit Units (ACCUs) for each tonne of abatement achieved. Farmers and landowners can earn ACCUs by changing land use or management practices to store carbon or reduce GHG emissions.

ACCUs can be sold to the government through a reverse auction, or to businesses wanting to offset their emissions. Projects must be registered with the Clean Energy Regulator before participating in an auction. During the bi-annual auctions, the projects that offer the lowest cost for emission reduction or sequestration are awarded contracts with the government to deliver ACCUs. The participants will receive payment for ACCUs delivered at the price they bid at auction. Since the creation of the ERF coincided with repeal of the carbon pricing mechanism, the government has remained the predominant purchaser of ACCUs. In place from 2012–15, the carbon pricing mechanism required Australia's largest carbon emitters to report and pay for the carbon emissions they produced.

The ERF allows for several methods that address three categories of forest carbon offsets: A/R, IFM, and AD. These methods include:

- Human-induced regeneration of permanent even-aged forest: this methodology requires that native forest growth be suppressed for 10 years prior to application; plans can include the exclusion of livestock or management of grazing, managing feral animals, managing invasive species and not engaging in mechanical or chemical control of native forest regrowth
- Avoided clearance of regrowth requires that project area contains native forest cover, that the landowner has an unrestricted clearing permit and that the land has been cleared at least twice in the past; baselines are generated using the Australian Full Carbon Accounting Model
- Native forest from managed regrowth: regenerating native forest on land where forest has previously been cleared for pastoral purposes
- Plantation forestry: for establishing a new plantation on land that had no plantation forest for at least 7 years or converting from a short-rotation to a long-rotation
- Avoided deforestation: avoiding clearing of forest that is permitted for converting to grassland or cropland
- Reforestation and afforestation require planting seedlings on cleared land that has been used for grazing, cropping or fallow for the prior 5 years
- Verified carbon standard (VCS) projects: projects avoiding harvest of native forest for wood products, where previously approved under the VCS
- Environmental or mallee plantings, which provides for planting a permanent (non-harvest) forest with a mixture of native species, or mallee trees[13]
- Farm forestry, which provides for planting permanent or rotational harvest trees on land previously clear of forest cover and used for agricultural purposes.

REDD+

The Reducing Emissions from Deforestation and forest Degradation (REDD) initiative, launched in 2008, is different from other voluntary standards in that it is a mechanism developed by parties to the UNFCCC and is not owned by any particular offset issuing body. REDD+ is a collaboration between the United Nations Development Programme (UNDP) and the United Nations Environment Programme (UNEP), with technical expertise of the Food and Agriculture Organization of the United Nations (FAO).

The + added to the REDD in 2011 signifies there is also a focus on enhancing forest carbon stock. Developing countries party to the UNFCCC are encouraged to combat climate change and reverse forest cover loss under REDD+ through five activities:

- Reducing emissions from deforestation
- Reducing emissions from forest degradation
- Conservation of forest carbon stocks
- Sustainable management of forests
- Enhancement of forest carbon stocks

For a country to receive results-based finance from the implementation of REDD+ activities, it must have:

- a national REDD+ strategy or action plan

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[13] 'Mallee' refers to low-growing shrubby Australian eucalyptus, which are part of the native vegetation in southern Australia.

- an assessed forest reference emission level (FREL) and/or forest reference level
- a national forest monitoring system
- a system for providing information on how the safeguards are being addressed and respected
- engaged in result-based actions that are measured, reported and verified (MRV)

The MRV process involves two separate assessments for (i) the proposed FREL, and (ii) the results of REDD+ actions. Information provided in the second assessment must be transparent, complete, accurate, and consistent with the FREL assessed and the guidelines for REDD+ results; it must be annexed to the biennial report of the country seeking REDD+ payments.

Verra, the organisation that runs VCS, has created a framework that serves as a comprehensive carbon accounting and verification platform to help jurisdictions guide the development of REDD+ projects and to help nest REDD+ projects within national jurisdictions. Under the VCS programme, projects are issued unique carbon credits known as Verified Carbon Units or VCUs. Each VCU represents a reduction or removal of one tonne of CO_2e achieved by a project.

Annex B. Carbon compliance markets

Three major compliance carbon markets allow forest offsets: New Zealand Emissions Trading System (NZ-ETS launched in 2008), California cap-and-trade system (2013) and China ETS (2021). Korea ETS also allows forest offsets but this has not yet resulted in the issuance of forest credits for Korean forest owners. Forest credits are envisaged in Canada, Mexico and the UK-ETS. The EU-ETS first wants to introduce a certification system for carbon removals, by 2023.

California

California has a legislated target of achieving GHG emissions reductions of 40% less than 1990 levels by 2030. One of the primary tools for achieving this is the California cap-and-trade system operated by the California Air Resources Board (CARB). The California market requires entities that emit more than 25 000 $MtCO_2e$/year to participate in the emission trading system.

Currently, 8% of each entity’s compliance obligation can be met with compliance offsets. This allowable amount will decline to 4% for the 2021-25 compliance period and will be set at 6% afterward. After 2021, half of the eligible compliance offsets will have to be sourced from California.

Under the CARB rules, it is possible to generate offsets for Afforestation/Reforestation (A/R), Improved Forest Management (IFM), and avoided deforestation (AD). As in other A/R schemes, project locations must have had less than 10% canopy cover of the prior ten years. Another option is reforestation after a natural disturbance that removed a minimum of 20% of the trees. IFM can qualify for offsets by increasing rotation ages, increasing stocking densities, and increasing forest productivity through thinning. AD can qualify for offsets with a registered conservation easement or a transfer of the property to public ownership.

CARB requires 100 years of monitoring. If a project fails to comply during the 100-year period, the forest owner is required to purchase offsets to make up for the lost sequestration.

Unlike other markets, California has methodologies available for urban forestry projects. These include:

- Increase urban forest productivity through thinning of diseased and suppressed trees
- Reducing emissions from avoided tree removal
- Planting additional trees on available and appropriate sites
- Monitoring and protecting trees to avoid premature mortality
- Reducing the vulnerability of trees to impacts of climate change by increasing resilience

As in the voluntary markets, offsets that are admitted into the California market must be real, permanent, quantifiable, verifiable, enforceable and additional (see Box A2.1). California carbon offsets tend to trade at a discount of around 5 to 15% to allowances.[14] This is because there is the risk of invalidation of the offsets for non-compliance with the offset protocols. As of December 2018, some 80% of the offsets registered under CARB were from forestry carbon sequestration projects.

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[14] In December 2018, allowances were trading around USD 15/tCO_2e.

New Zealand

The New Zealand Emissions Trading Scheme (NZ-ETS) began in 2008 and is one of the government's key tools for reducing GHG emissions. In the NZ-ETS, one New Zealand Unit (NZU) represents one metric tonne of CO_2e emissions. For every tonne of GHG emitted, polluters must surrender one NZU to the government. Designed to cover the whole economy, the scheme has broad sectoral coverage including liquid fossil fuels, stationary energy, industrial processors, waste, and forestry.

In June 2020, the New Zealand Parliament passed comprehensive legislative reforms to the scheme. The reforms enabled annual emissions caps to be set and adjusted over time, aligning with New Zealand's emission reduction targets.[15] Unit supply into the scheme is managed through an auctioning mechanism, with the first auction held in March 2021. Units are also supplied to eligible emissions intensive trade exposed firms through industrial allocation and to eligible forest owners for carbon sequestration.

The NZ-ETS provides an incentive for new forest planting and imposes liabilities for deforestation. The scheme differentiates between two classes of forest based on their date of establishment: pre-1990 and post-1989.

Pre-1990 forest land is land that was forested on 31 December 1989, remained forested on 31 December 2007, and on 31 December 2007 was predominately exotic forest species. Owners of pre-1990 forest land cannot earn units for sequestration but must pay for the emissions if the land is deforested (either converted to another land use, or forest fails to re-establish). Pre-1990 forest land which is predominately indigenous species on 31 December 2007 is not included in the ETS but is regulated and protected through the Resource Management Act and the Forests Act..

Post-1989 forest land is land with forests first established after 31 December 1989. Forest owners or the holders of forestry leases/rights can voluntarily register in the scheme and become participants. Participants earn 1 NZU for every tonne of CO_2 sequestered. Once registered, they are liable to surrender one unit for every tonne of emissions from the forest (for example, following harvesting). If a forest exits the ETS, it must surrender the current unit balance of forest (the net number of units received).

Forestry participants can sell units on the secondary market. Primarily this is an exchange with industry participants seeking to buy units to fulfil their surrender obligations. The obligations of participants with registered post-1989 forest include accounting for changes in a forest's carbon stock and filing emissions returns.

From 1 January 2023, post-1989 forest land will belong in one of three sub-classes:

- standard post-1989 forest (stock change), and will remain the approach for forests registered before 31 December 2022;
- standard post 1989 forest (averaging); and is the mandatory accounting method for standard post-1989 forests newly registered in the scheme from 1 January 2023; or,
- permanent post-1989 forest.

Stock change and averaging are two different methods for accounting for carbon stocks in forests. In stock change accounting, participants calculate carbon stock as their forest grows and is harvested, over the production cycle (as post-1989 forest does now). They earn units and pay them back in line with these changes in carbon stock.

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[15] New Zealand has a legislated domestic target of net zero emissions of all GHGs other than biogenic methane by 2050, and 24–47% reduction below 2017 biogenic methane emissions by 2050, including 10% below 2017 biogenic methane emissions by 2030. New Zealand's current target under the Paris Agreement is to reduce GHG emissions by 30% below gross emissions for the period 2021-30.

In averaging accounting, participants earn units for carbon sequestered as their forest grows up to a pre-determined long-term average of carbon storage. Thereafter, participants will neither earn more units nor be liable for paying back units at harvest time. The details of how averaging accounting will apply are being developed through regulations, and are expected to be confirmed in October 2022.

The introduction of averaging accounting in the recent reforms was designed to increase the incentive for new afforestation, primarily by removing harvesting liabilities faced by forest participants. It also better aligns forestry unit allocations with New Zealand's accounting approach for forestry under the Paris Agreement.

The recent reforms also introduced a permanent post-1989 activity that will be available from 2023 as an alternative to the standard post-1989 forest activity. Forests can be registered directly into the permanent post-1989 activity, or move from standard forestry into the activity. Participants will receive units for the carbon stock change in their forests (stock change accounting) but will not be able to clear-fell harvest for at least 50 years. Participants will face significant financial penalties if they clear fell-harvest or deforest the forest land, in addition to surrendering units for the emissions.

Korea

Korea's GHG Emissions Trading Scheme (KETS) was launched in 2015. It is a cap-and-trade system that, as of March 2021, applied to 684 companies including 5 domestic airlines that account for approximately 73% of the nation's GHG output.

Companies are allowed to use offsets for up to 5% of their obligations. A variety of forest carbon methodologies are allowed. These include:

- Afforestation and reforestation
- Forest management
- Forest revegetation
- Wood product utilisation
- Burned area rehabilitation

International offset projects developed by Korean firms are eligible within KETS. The current carbon price for Korean Allowance Unit (KAU) -- equivalent one tCO_2 allowance - is some KRW 19 000 (some USD 20).

Japan

Under the Joint Crediting Mechanism (JCM), Japan purchases carbon credits from projects in partner countries to meet its emission reduction obligations (government-to-government co-operation). Bangladesh, Cambodia, Chile, Costa Rica, Ethiopia, Indonesia, Kenya, Laos, Maldives, Mexico, Mongolia, Myanmar, Palau, Philippines, Saudi Arabia, Thailand, Vietnam have signed bilateral agreements to this effect. The prefectures of Tokyo and Saitama launched offset mechanisms alongside their ETS, in 2010 and 2011 respectively. In Saitama, one offset mechanism focuses on forest plantation and forest maintenance projects, the other on renewable energy projects. The Tokyo offset mechanism covers energy efficiency and renewable energy projects, including outside Tokyo Prefecture. The J-credit scheme aims to support voluntary initiatives to reduce GHG emissions in Japan. J-credits from forestry projects can also be used for compliance under the Saitama ETS.

Other markets

There are other markets that are either operational and do not allow forest offsets or are yet to be fully operational. As the world's largest carbon market, the European Union Emissions Trading System (EU-ETS) has long been the main source of demand for international (CDM and JI) credits (1 058 $MtCO_2e$ in 2008-12).[16] Credits are accepted for most projects, but not for afforestation or reforestation (LULUCF) projects. Since 2013, credits must be exchanged for EU-ETS emission allowances within the limits of individual rights. The EU does not currently plan to continue using international credits after 2020. In contrast, Swiss companies that produce or import fossil fuels can use carbon credits, including from forestry projects abroad, to meet their compliance obligations under Swiss CO_2 law.[17]

Following pilot ETSs in eight provinces, China launched a national ETS in January 2021, becoming the largest ETS in the world (over 4 000 $MtCO_2e$, or around 40% of national emissions). Regulated entities (electricity sector) will have to surrender allowances for their 2019-20 emissions in 2021. Compliance obligations are however limited and intensity-based (adjusted ex post according to production levels). Entities covered by the national ETS can use national carbon credits - Chinese Certified Emission Reduction Offsets (CCERs) - up to 5% of their verified emissions. Entities covered by provincial ETS can use provincial carbon credits where applicable (e.g. Beijing, Fujian and Guangdong). Forestry projects are authorised for both national and provincial carbon credits (this is even the sole focus of Beijing and Fujian provincial credits). The provincial pilot ETSs should gradually be integrated into the national ETS as its sector coverage expands. National and provincial carbon credits should also be gradually integrated.

Canada is developing a federal GHG offset system, building on the Pan-Canadian GHG Offsets Framework agreed between federal, provincial and territorial governments in 2018.[18] Offset project would need to occur in Canada and would include any land use, land use change, and forestry activities. The aim is to increase the supply of compliance units in the federal Output-Based Pricing System (OBPS), which currently regulates GHG trading for industry, thereby reducing compliance cost while creating incentives for voluntary GHG mitigation projects. The credits would be tradeable in the same manner as OBPS surplus credits. The federal system would not replace provincial offset systems (Alberta, British Columbia, Québec), but would complement them, the OBPS regulations allowing recognised units from provincial/territorial offset systems to be used for compliance.

Mexico plans to set up a national carbon credits mechanism for entities covered by its new emissions trading system. Eligible activities have not yet been defined but forestry should be included (forest offset protocols have been developed).

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[16] https://ec.europa.eu/clima/policies/ets/credits_en, accessed 29 May 2021.

[17] The Swiss ETS was linked to the EU-ETS in January 2020.

[18] https://www.canada.ca/en/environment-climate-change/services/climate-change/pricing-pollution-how-it-will-work/federal-offset-system.html.

Annex C. Factors of cost and quantity of forest carbon sequestration by country

Table A C.1. Factors of cost and quantity of forest carbon sequestration by country

No.	Country	Land use cost[1]	Average Normalised Difference Vegetation Index (NDVI)[2]	Ease of Doing Business Index[3]	Emissions of alternative land use[4]	Wildfire risk[5]	Labour cost[6]
1	Afghanistan	115	0.174	38.440	0.251	0.001	2741
2	Albania	2085	0.548	63.025	2.127	0.004	12751
3	Algeria	446	0.380	45.528	0.188	0.008	15367
4	Angola	145	0.662	38.078	0.113	0.251	12309
5	Argentina	225	0.533	57.096	0.820	0.010	34960
6	Armenia	1148	0.449	70.423	1.031	0.008	11095
7	Australia	81	0.596	80.456	0.291	0.020	121598
8	Austria	2005	0.660	78.793	2.274	0.000	114095
9	Azerbaijan	695	0.506	65.509	1.581	0.019	11906
10	Bahamas	7774	0.589	57.559	1.581	0.005	69424
11	Bahrain	11085	0.090	68.150	3.500	0.002	39255
12	Bangladesh	2769	0.600	41.162	9.361	0.005	2886
13	Barbados	5086	0.787	57.704	3.310	0.000	33767
14	Belarus	571	0.590	71.643	1.959	0.003	13418
15	Belgium	2716	0.664	72.340	6.187	0.003	125107
16	Belize	1275	0.828	55.337	1.357	0.022	11484
17	Benin	880	0.561	49.985	1.792	0.208	3131
18	Bhutan	535	0.779	65.207	1.185	0.004	6205
19	Bolivia	80	0.534	50.319	0.395	0.011	6576
20	Bosnia-Herzegovina	576	0.668	64.737	0.930	0.003	19148
21	Botswana	14	0.388	65.612	0.190	0.032	20292
22	Brazil	360	0.692	55.486	1.696	0.012	24128
23	Brunei Darussalam	9400	0.841	62.663	7.858	0.011	69626
24	Bulgaria	518	0.614	71.916	0.760	0.006	19749
25	Burkina Faso	294	0.365	50.908	1.334	0.067	2259
26	Burundi	461	0.678	45.722	0.499	0.093	698
27	Cabo Verde	1885	0.375	53.606	1.442	0.002	10255
28	Cambodia	870	0.675	53.140	5.253	0.058	1922
29	Cameroon	468	0.633	42.904	2.537	0.091	3632
30	Canada	445	0.509	79.533	0.830	0.004	99679
31	Central African Republic	149	0.715	32.107	31.898	0.248	1378
32	Chad	123	0.394	35.611	0.573	0.120	2444
33	Chile	593	0.580	71.569	0.894	0.008	32827
34	China	1538	0.569	64.321	1.842	0.009	11197
35	Colombia	463	0.761	69.020	1.438	0.008	15675
36	Comoros	2467	0.558	46.497	0.944	0.009	6690

No.	Country	Land use cost[1]	Average Normalised Difference Vegetation Index (NDVI)[2]	Ease of Doing Business Index[3]	Emissions of alternative land use[4]	Wildfire risk[5]	Labour cost[6]
37	Congo Democratic Republic	242	0.729	34.439	1.451	0.071	5875
38	Congo Republic	55	0.741	38.410	0.281	0.207	1551
39	Costa Rica	1508	0.807	68.218	1.422	0.010	25554
40	Croatia	1541	0.658	72.039	2.026	0.003	40428
41	Cyprus	4533	0.516	72.184	3.430	0.003	50622
42	Czech Republic	1192	0.622	76.306	1.681	0.000	47534
43	Denmark	1599	0.602	84.562	3.647	0.001	136373
44	Djibouti	19	0.190	47.431	0.347	0.007	6948
45	Dominican Republic	1571	0.766	58.242	2.310	0.007	16747
46	Ecuador	1238	0.752	57.373	1.961	0.003	13327
47	Egypt	8948	0.499	55.325	8.686	0.013	10104
48	El Salvador	896	0.735	63.255	1.805	0.012	9546
49	Equatorial Guinea	848	0.766	39.594	0.065	0.003	49669
50	Estonia	777	0.564	80.670	1.313	0.001	42155
51	Ethiopia	559	0.480	44.665	2.095	0.046	1270
52	Fiji	990	0.859	61.802	2.135	0.014	13689
53	Finland	2823	0.514	80.062	2.115	0.000	116569
54	France	1534	0.671	76.136	2.358	0.001	111072
55	Gabon	132	0.763	44.150	0.088	0.009	34910
56	Gambia	686	0.501	47.249	1.599	0.213	2486
57	Georgia	520	0.596	80.702	1.433	0.004	10050
58	Germany	1879	0.668	79.468	3.442	0.001	101809
59	Ghana	685	0.686	57.802	1.850	0.128	4393
60	Greece	1258	0.590	67.043	1.012	0.006	72855
61	Guatemala	1556	0.775	61.721	1.485	0.027	9694
62	Guinea	104	0.657	45.674	2.154	0.279	2511
63	Guinea Bissau	308	0.650	42.049	1.052	0.145	1930
64	Guyana	294	0.814	54.694	1.577	0.017	11162
65	Haiti	894	0.697	37.721	1.895	0.002	2138
66	Honduras	757	0.729	55.917	2.024	0.020	6352
67	Hungary	991	0.579	71.710	1.147	0.003	36556
68	Iceland	522	0.357	78.991	0.288	0.003	101234
69	India	1843	0.528	57.123	3.018	0.005	4179
70	Indonesia	2120	0.771	64.547	2.714	0.013	6938
71	Iran	861	0.259	55.594	0.899	0.004	18139
72	Iraq	980	0.242	43.874	0.645	0.006	19014
73	Ireland	622	0.759	80.001	4.023	0.000	145262
74	Israel	7536	0.366	73.846	3.991	0.004	88812
75	Italy	3206	0.630	72.235	2.005	0.004	106676
76	Ivory Coast	347	0.710	51.425	0.226	0.140	5898
77	Jamaica	1958	0.754	67.075	2.282	0.002	13335
78	Japan	13755	0.679	77.827	8.305	0.005	84990
79	Jordan	1480	0.223	57.896	0.868	0.013	19612
80	Kazakhstan	41	0.285	74.215	0.121	0.044	21400
81	Kenya	576	0.625	62.070	0.933	0.018	3642
82	Korea	16127	0.615	83.673	10.202	0.006	54211
83	Kuwait	3851	0.107	60.805	1.800	0.026	66126
84	Kyrgyz Republic	101	0.326	61.649	0.362	0.010	3273
85	Laos	955	0.799	49.083	3.816	0.055	3640
86	Latvia	542	0.564	79.909	0.980	0.001	35576

No.	Country	Land use cost[1]	Average Normalised Difference Vegetation Index (NDVI)[2]	Ease of Doing Business Index[3]	Emissions of alternative land use[4]	Wildfire risk[5]	Labour cost[6]
87	Lebanon	2582	0.432	54.511	1.056	0.003	27745
88	Lesotho	60	0.414	57.253	0.450	0.030	3374
89	Liberia	436	0.773	41.175	0.229	0.045	1845
90	Libya	119	0.181	32.532	0.099	0.000	24678
91	Lithuania	548	0.576	79.615	1.448	0.001	36992
92	Luxembourg	1283	0.687	69.305	9.467	0.007	276439
93	Madagascar	80	0.593	43.675	0.500	0.078	1029
94	Malawi	334	0.592	54.152	0.689	0.066	971
95	Malaysia	3677	0.825	78.551	1.891	0.016	21828
96	Maldives	24555	0.721	52.676	0.323	0.005	19183
97	Mali	118	0.374	51.923	0.556	0.121	2491
98	Malta	12995	0.544	64.091	7.748	0.019	61076
99	Mauritania	27	0.227	46.363	0.173	0.017	7662
100	Mauritius	4825	0.784	77.136	1.663	0.005	22123
101	Mexico	367	0.599	72.185	0.814	0.027	25647
102	Moldova	380	0.503	72.213	0.503	0.008	10002
103	Mongolia	12	0.240	66.279	0.085	0.014	8370
104	Montenegro	931	0.598	71.890	0.000	0.004	24605
105	Morocco	446	0.327	68.615	0.348	0.001	9567
106	Mozambique	76	0.634	52.555	0.055	0.144	1385
107	Myanmar	1418	0.721	42.589	5.699	0.041	2275
108	Namibia	23	0.341	60.411	0.185	0.070	17664
109	Nepal	1480	0.686	59.239	5.447	0.006	1469
110	Netherlands	8397	0.690	75.727	8.253	0.002	111131
111	New Zealand	1169	0.788	87.108	3.368	0.000	82703
112	Nicaragua	373	0.723	54.179	1.488	0.023	4729
113	Niger	63	0.236	48.941	0.102	0.004	1320
114	Nigeria	1398	0.550	49.625	1.008	0.113	8449
115	North Macedonia	909	0.577	79.613	0.823	0.003	17156
116	Norway	6939	0.543	82.283	3.926	0.001	170888
117	Oman	772	0.112	67.658	0.657	0.006	32113
118	Pakistan	1585	0.369	51.954	3.208	0.008	3698
119	Panama	606	0.778	65.304	1.658	0.007	30319
120	Papua New Guinea	3120	0.844	58.230	0.448	0.010	8651
121	Paraguay	189	0.697	58.021	0.836	0.038	11414
122	Peru	537	0.500	67.501	0.736	0.002	11344
123	Philippines	2430	0.784	58.940	3.660	0.008	6690
124	Poland	950	0.596	77.489	2.179	0.001	32893
125	Portugal	1334	0.610	76.511	1.920	0.018	53730
126	Puerto Rico	4235	0.745	69.259	3.473	0.002	97805
127	Qatar	3217	0.079	65.979	2.494	0.001	80134
128	Romania	747	0.592	72.872	1.098	0.004	24926
129	Russia	299	0.493	75.300	0.337	0.012	26347
130	Rwanda	1211	0.662	69.033	1.082	0.034	1510
131	Samoa	2169	0.868	60.768	3.519	0.011	16348
132	Sao Tome and Principe	699	0.763	44.242	0.209	0.002	5337
133	Saudi Arabia	94	0.135	60.230	0.029	0.001	52892
134	Senegal	310	0.411	51.284	1.172	0.117	5548
135	Serbia	961	0.622	72.331	0.000	0.002	19034
136	Sierra Leone	528	0.739	47.069	1.381	0.212	1814
137	Singapore	144938	0.776	85.302	94.119	0.009	92576

No.	Country	Land use cost[1]	Average Normalised Difference Vegetation Index (NDVI)[2]	Ease of Doing Business Index[3]	Emissions of alternative land use[4]	Wildfire risk[5]	Labour cost[6]
138	Slovakia	1290	0.630	75.008	1.323	0.001	40443
139	Slovenia	1651	0.689	75.506	3.053	0.000	57762
140	South Africa	89	0.493	65.658	0.358	0.077	23582
141	Spain	1376	0.590	77.062	1.330	0.006	82838
142	Sri Lanka	2313	0.770	59.652	3.355	0.005	8742
143	St. Lucia	3964	0.787	63.518	3.307	0.000	24161
144	St. Vincent and Grenadines	4864	0.787	57.005	1.759	0.000	17741
145	Sudan	354	0.271	45.117	2.486	0.054	6357
146	Suriname	5339	0.830	47.078	7.597	0.005	26618
147	Sweden	2811	0.606	81.986	2.167	0.000	122675
148	Switzerland	3164	0.635	76.486	3.027	0.000	162080
149	Tajikistan	336	0.277	53.207	0.972	0.004	3333
150	Tanzania	297	0.615	52.514	0.652	0.082	1826
151	Thailand	1880	0.687	74.399	3.530	0.040	10177
152	Togo	348	0.601	47.928	1.278	0.247	1389
153	Trinidad and Tobago	3524	0.698	61.305	4.395	0.010	37127
154	Tunisia	419	0.338	65.135	0.392	0.001	13440
155	Turkey	1681	0.442	69.813	1.201	0.006	37104
156	Uganda	415	0.722	57.265	1.867	0.062	2062
157	Ukraine	312	0.516	65.895	0.483	0.017	8979
158	United Arab Emirates	6751	0.105	77.673	2.723	0.005	50731
159	United Kingdom	1094	0.689	83.298	2.400	0.002	98516
160	United States	472	0.592	83.591	0.910	0.002	120096
161	Uruguay	251	0.656	60.631	1.807	0.001	30950
162	Uzbekistan	690	0.318	63.461	0.917	0.009	4273
163	Vanuatu	985	0.881	60.389	1.775	0.002	7798
164	Vietnam	2695	0.735	64.957	7.003	0.016	3304
165	Zambia	82	0.584	61.646	0.317	0.203	4129
166	Zimbabwe	92	0.504	48.063	0.593	0.078	2972

Notes:
1. Land use cost (USD/ha/year) is proxied by the agricultural value added per hectare of agricultural land.
2. National averages for NDVI and fire risk are intended for cross-country comparison, although they mask in-country heterogeneity.
3. The higher the number, the better the ease of doing business.
4. Emissions of alternative land use (tCO_2e/ha/year) is proxied by GHG agricultural emission per hectare of agricultural land.
5. The higher the number, the greater the risk of wildfire.
6. Labour cost (USD/person/year) is proxied by the economy's value added per employed person.
Source: Authors.

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