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A global analysis of the break-even prices to reduce atmospheric carbon dioxide via forest plantation and avoided deforestation

Long Chu [a], R. Quentin Grafton [a,*], Hai Nguyen [b]

[a] Crawford School of Public Policy, the Australian National University, Canberra 2601, Australia
[b] College of Science, Health, Engineering and Education, Murdoch University, Perth 6150, Australia

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ABSTRACT

A cross-country assessment of the cost of carbon sequestration in the forest sector is needed for planning and achieving climate commitments, such as the Paris Agreement, at global, regional, national, or sectoral scales. We provide a global and bottom-up assessment of the break-even carbon price to undertake forest plantation and forest conservation at a country level for 166 nations. We construct a global dataset of key cost factors, examine their global distributions, and undertake a cross-country assessment of cost differences with alternative forest programs (plantation and conservation). Our bottom-up approach is also calibrated to sub-national case studies to investigate the average cost of forest carbon in Australian states and Canadian provinces. We find that the break-even carbon price varies by countries, locations within a country, forest programs and co-benefits. Our estimates provide an approximation of the cost-effectiveness of forest carbon sequestration relative to non-forest climate mitigation approaches.

1. Introduction

Human activities have resulted in more than a 1.0 °C increase in the global mean surface temperature above pre-industrial 1850–1900 levels (Allen et al., 2018:p.51), causing an economic loss between 0.2 and 2.0% global GDP (IPCC, 2014:p.73), i.e., around 170–1700 billion dollars in 2019 value. In addition to the economic costs, climate change is generating dangerous impacts to terrestrial, ocean, and coastal ecosystems (García Molinos et al., 2017; Gudmundsson et al., 2017; Taylor et al., 2017; Turco et al., 2018; Smale et al., 2019; van den Brink et al., 2019). Without stringent and immediate mitigation, the current trend in greenhouse gas (GHG) emissions will lead to an increase in average surface temperature of about 0.2 °C per decade (Allen et al., 2018:p.51) and increasingly large socio-economic consequences (Hoegh-Guldberg et al., 2018; Lin et al., 2018; Liu et al., 2018; Naumann et al., 2018; Madakumbura et al., 2019).

Anthropogenic global warming is driven by excessive GHG emissions, mainly carbon dioxide (CO_2). Between 1750 and 2010, cumulative anthropogenic GHG emissions were 2040 ± 310 billion tons, of which more than 90% was from fossil fuel burning and nearly 10% from land-use change (IPCC, 2014b:f. SPM1.d). Some 30% of the GHG emissions have been sequestered in plants and soil; 30% have been absorbed by oceans; and around 40% (880 ± 35 $GtCO_2$) has been added to the atmosphere (IPCC, 2014b:p.4).

Forests play important roles in climate change mitigation for two key reasons (van Kooten, 2020). First, deforestation has caused nearly 10% of the total GHG emissions (IPCC, 2014b), so conservation of forests (including avoided deforestation and improved forest management) limits GHG emissions. Second, forest plantation is an important approach to sequester carbon from the atmosphere (de Coninck et al., 2018:p.394–395). Forest plantation includes afforestation and reforestation, and both help with carbon dioxide removal via the biological photosynthetic of trees.

Given the vital role of forests in climate change mitigation, it is critically important to assess the costs of forest programs which help sequester carbon from the atmosphere or avoid emissions from deforestation (referred to as forest carbon). Previous studies have developed analytical framework to determine the costs of carbon sequestration in forest programs (e.g., Stavins, 1999; Sohngen and Mendelsohn, 2003; Sathaye et al., 2006; Tavoni et al., 2007; Favero et al., 2020). In Table 1, we list the estimated cost of carbon in forest programs from selected studies, together with the impact on carbon dioxide emissions. These estimates vary from less than USD 2 to 100/tCO_2, depending on the targeted quantity, the base year, and scale.

* Corresponding author.
E-mail addresses: long.chu@anu.edu.au (L. Chu), quentin.grafton@anu.edu.au (R.Q. Grafton), hai.nguyen@murdoch.edu.au (H. Nguyen).

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There is a growing volume of literature on the marginal costs of climate change abatement at global and regional scales. Recent estimates show that the costs of forest-based carbon vary with the targeted sequestration quantity, a relatively low cost at small levels of carbon sequestration but likely to rise rapidly with much larger volumes of carbon sequestered (e.g., Su et al., 2017; Busch and Engelmann, 2018; Zhang et al., 2019; Austin et al., 2020; Kuosmanen et al., 2020; Stahlke, 2020). Some alternative carbon dioxide removal techniques have also started commercialisation with increasingly competitive average costs, such as bioenergy with carbon capture and storage (BECCS) and direct air capture (DAC) (Fuss et al., 2018). Other techniques, such as ocean fertilisation and alkalinisation or enhanced weathering are in an early stage of development (Pires, 2019). Forests and other land-use sectors can play an important role in achieving global climate mitigation targets (Roe et al., 2019). How large is this role depends crucially on estimates of the average large-scale costs of forest-based climate mitigation of potential sequestration that vary across countries and sub-national regions.

Here, we provide complementary first-order approximation of the average forest-based carbon costs of carbon mitigation via sequestration. Our cost estimates are based on the premise that forest programs use inputs, e.g., land and labour, to sequester carbon or to avoid forest deforestation or degradation that generate carbon dioxide emissions. We estimate the break-even prices for forest carbon programs, defined as the minimum a country would be willing to accept to sequester carbon to just cover the forest plantation or forest conservation costs associated with forest carbon sequestration.

Our contribution is to undertake a bottom-up cross-country assessment of the average cost of carbon in forest plantation and conservation by identifying the key cost factors and examining their global distributions. We combined several global databases to construct a global dataset of all these cost factors for 166 countries. We then used this dataset to calculate how the cost factors interact to determine the cross-country distribution of the break-even price for forest carbon sequestration while accounting for differences in forest programs (plantation and conservation) and forest co-benefits.

We respond, at a country level, to four key policy questions: (1) What are the key cost factors in sequestering carbon (and avoiding emissions) in forests? (2) How do these cost factors vary across countries? (3) Which countries (or group of countries) are, on average, low-cost locations (with smaller break-even price)? and (4) How might the break-even price for forest carbon sequestration be reduced? An adequate response to these questions is needed to help cost-effectively deliver climate change mitigation from forests at global, regional, national or sectoral scales (Global Commission on the Economy and Climate, 2015; Pavani et al., 2018; Sloan et al., 2018; Yousefpour et al., 2018; Glanemann et al., 2020). Our estimates of national forest carbon costs also assist with comparisons in delivering on Nationally Determined Contributions (NDCs) and alternative mitigation pathways (Münnich Vass, 2017; Hepburn et al., 2019). We also show how our bottom-up approach can be used to estimate break-even prices of forest carbon across countries and at a sub-national level in Australia and Canada.

Table 1
Forest carbon costs (USD) of carbon dioxide emission reductions, selected studies.

Category	Forest type	Scale	Period	Expected annual emission reduction (Gt CO_2)	Costs to achieve expected annual reduction (USDt^{-1} CO_2)	Price year	Sources
Avoided deforestation	Tropic	Global	2020–2050	1.8–3.6*	20–50	2020	Busch et al. (2019)
		Global	2016–2050	1.2–2.3*	20–50	2014	Busch and Engelmann (2017)
		Global	2020–2050	2.8	30	NA	Sohngen (2009)
		Global	2007–2037	1.9	2.3	2007	Greig-Gran (2008), Murray et al. (2009)
		Global	2005–2030	1.6–4.3	20	2005	Kindermann et al. (2008)
				3.1–4.7	100		
		Africa	2005–2030	0.9–1.5	20		
				1.4–1.7	100		
		Latin America	2005–2030	0.8–1.7	20		
				1.1–1.9	100		
		Southeast Asia	2005–2030	0.1–1.1	20		
				0.3–1.1	100		
		Global	NA	3.2–6.4	5.5	2005	Strassburg et al. (2008)
		Eastern and Southern Africa	2007–2030	0.4			
		Northern Dry Africa		0.1			
		Western and Central Africa		0.6			
		South SE Asia and Pacific		0.7			
		Central America and Mexico		0.3			
		South America		1.5			Blaser and Robledo (2007)
		Other regions		0.2	2.8	2007	
	Tropical and temperate	Global	2010–2100	0.09–2.0*	5–100	2010	Sathaye et al. (2006)
Forestation	Tropic	Global	2020–2050	0.2–0.5*	20–50	2018	Busch et al. (2019)
	Tropic	Global	2020–2050	1.1	30	2009	Sohngen (2009)
	Temperate	Global	2020–2050	0.8	30	2009	Sohngen (2009)
	Tropic and temperate	Global	2010–2100	1.4–3.1*	5–100	2010	Sathaye et al. (2006)
	Tropic	Global	2010-2100	0.4–1.1*	1.9–51.1	2010	Sohngen and Mendelsohn (2003)
Enhancement	Temperate	Global	2020–2050	1.4	30	2009	Sohngen (2009)
	Tropic	Global	2020–2050	0.7	30	2009	Sohngen (2009)
		Tropical and non-annex 1 countries	2030	1.8	1.2	NA	Blaser and Robledo (2007)

Note: * Annual emission reduction calculated from original cumulative emission reduction.

Our paper is organised as follows. In section 2, we delineate an economic modelling framework to estimate a first-order approximation of the break-even price of forest carbon. Section 3 describes how we construct the cross-country dataset of these cost factors. Section 4 presents the results of the cross-country analyses, including the global distribution of the cost factors and the break-even price to undertake forest carbon across 166 countries. Section 5 presents the results of the two sub-national case studies in Australia and Canada. Section 6 discusses the policy implications of the results, and section 7 concludes.

2. Modelling framework

Our model distinguishes two broad categories of forest programs, namely conservation (e.g., avoided deforestation and forest management) and forest plantation. Forest plantation programs are further classified into afforestation and reforestation in the calibration process to take into account their possible differences in forest co-benefits. For each category, we combine practical carbon offset protocols of VERRA and Gold Standard with previous studies (McMahon et al., 2010; Busch et al., 2019) to be able to incorporate wildfire risk, which varies across countries, and which affects the break-even price for forest carbon sequestration. To be comparable to the carbon offset protocols, the dynamics feature in our model is formalised in a discrete-time setting, as an analogy to continuous-time models with possible discrete events of the impact of forest co-benefit and bushfire risk on forest rotation (Hartman, 1976; Reed, 1984).

We use the subscript c as the country index and denote r^c as the probability of wildfire in one year in country c. Let T be the duration of the forest program and w_t^c be a variable which takes the value 1 if a wildfire occurs at time t and zero otherwise, noting that w_t^c follows a Bernoulli distribution in eq. (1).

$$w_t^c \sim Bernoulli(r^c) \text{ with } t = 1..T \tag{1}$$

2.1. Forest plantation

For forest plantation programs, the stochastic dynamics of tree age is specified by eq. (2) when a_t^c denotes the tree age at time t. At the start of the forest plantation program, the tree age is zero, and the age increases (by one every year) if a wildfire does not occur. When a wildfire occurs, we assume that plantation restarts on the burned parcel of land.

$$a_{t+1} = \begin{cases} a_t + 1 \ if w_t^c = 0 \\ 0 \ if \ w_t^c = 1 \end{cases} \text{ with } t = 1..T \tag{2}$$

subject to eq. (1) and the initial condition $a_t = 0$ when $t = 0$.

We suppose that a country is offered a carbon price p for carbon sequestered in plantation programs such that the net benefit of the program at time t in country c is formalised in eq. (3) where the superscript '*plan*' signifies a forest plantation program. In eq. (3), u^c is land-use cost, X^c is a set of country-specific scale factors, e.g., rainfall and temperature, that determine the average carbon stock per unit of land with a mature forest, both above and below ground; e^c is the avoided emissions from alternative land use; $tran^c$ is the ratio of transaction costs that can be as much as 45% of total costs (Milne, 1999); ω^c is the cost of planting trees; $s(a_t^c|X^c)$ is the carbon storage per unit of land with forest age a_t^c in a given X^c, such that $s(a_t^c|X^c) - s(a_{t-1}^c|X^c)$ is the change in carbon storage stock between a year and the previous year in country c; and $b(a_t^c|X^c)$ is the forest co-benefit (other than from carbon sequestration) in country c which depends on the tree age.

The first term in the RHS of eq. (3) is the carbon benefit which equals the carbon quantity times carbon price. The second term is the co-benefit (other than carbon sequestration), and the third term presents the cost of the forest planation program, and which includes transaction costs.

$$\Pi_t^{c,plan}\left(a_t^c, w_t^c | p, u^c, X^c, e^c, tran^c, r^c, \omega^c\right) = \tag{3}$$

$$\begin{cases} p\left(s\left(a_t^c|X^c\right) - s\left(a_{t-1}^c|X^c\right) + e^c\right) + b\left(a_t^c|X^c\right) - \left(u^c + \omega^c w_t^c\right)\left(1 + tran^c\right) \ with \ t = 1..T-1 \\ -\omega^c\left(1 + tran^c\right) \ when \ t = 0 \end{cases}$$

The carbon storage per unit of land with forest age a_t^c in a given X^c is specified using tree-growth allometric function in eq. (4). In this equation, X_1^c is the country-specific ratio of below-ground carbon stock to above-ground carbon stock, X_2^c and X_3^c are the shift and curvature parameters. This country-specific function can be approximated using the country-level dataset for above and below-ground forest carbon growth rates published by Cook-Patton et al. (2020: supplementary data) and the calibration approach in the spatially disaggregated forest model published by Busch et al. (2019:methods section).

$$s\left(a_t^c|X^c\right) = \left(1 + X_1^c\right)X_2^c\left(a_t^c\right)^{X_3^c} \tag{4}$$

The expectation of the net present value generated by the plantation program during its lifespan is represented by eq. (5). In this equation, ρ is the discount rate, and the operator E_{w^c} is the expectation over all possible realisations of the uncertainty w_t^c during the lifespan of the program. Tree age is given by a Markov process and the net present value can be formalised in a Bellman's recursive form in eq. (6) where, for compactness, the dot in this equation represents the corresponding set of country-specific factors in eq. (5).

$$V_0^{c,plan}\left(a_0^c | p, u^c, X^c, e^c, tran^c, r^c, \omega^c\right) = E_{w^c} \sum_{t=0}^{T} \frac{1}{(1+\rho)^t} \Pi_t^{c,plan} \left(a_t^c, w_t^c | p, u^c, X^c, e^c, tran^c, r^c, \omega^c\right) \tag{5}$$

subject to (2)

$$V_t^{c,plan}\left(a_0^c|p,.\right) = \Pi_t^{c,plan}\left(a_t^c|p,.\right) + \frac{1}{1+\rho} E_{w_t^c} V_{t+1}^{c,plan}\left(a_{t+1}^c|p,.\right) \tag{6}$$

The (expected) net present value, $V_0^{c,\,plan}$ in eq. (5) or eq. (6), can be positive or negative, depending on country-specific factors and the offered carbon price (p). The break-even price is defined in eq. (7). This is the minimum payment that country c would be prepared to receive in the form of a carbon price for forest carbon sequestration in its plantation forests. Mathematically, this break-even price is an implicit function of the country-specific factors, which can be positive or negative, depending on the cost factors and forest co-benefits that arise other than from carbon. There is no closed-form solution for the implicit function of the break-even price in eq. (7), and the solution must rely on numerical techniques.

$$V_0^{c,plan}\left(a_0^c | p^{c,plan}(.),.\right) = 0 \tag{7}$$

2.2. Forest conservation

In forest conservation programs, trees are standing at the commencement of the carbon price payment. We denote $\overline{a}^c$ as the starting age of trees, noting that their age increases if wildfire does not occur. When a wildfire occurs, we assume that trees will be replanted on the burned parcel of land. Thus, the dynamics of tree age is specified in eq. (8).

$$a_{t+1}^c = \begin{cases} a_t^c + 1 \; if \, w_t^c = 0 \\ 0 \; if \; w_t^c = 1 \end{cases} \text{when } t = 1..T \tag{8}$$

subject to eq. (1) and the initial condition $a_t^c = \overline{a}^c$ when $t = 0$.

The net benefit of the conservation program at time t is formalised by eq. (9) where the superscript '*cons*' signifies forest conservation programs. The difference between eq. (9) and eq. (3), which defines the net benefit of plantation program, is the starting age of trees and the net benefit at time zero. For instance, at the commencement of a forest plantation program there are no carbon benefits from trees but there is an initial cost of plantation. By contrast, a forest conservation program does not incur an initial cost of plantation.

The net benefit of conservation at the beginning of the program is the avoided emissions from harvesting existing stand that would occur in the Business-As-Usual (BAU) scenario where forest land is converted to other purposes. This avoided emission is part of the total carbon stock because a fraction (γ) of above-ground carbon in trees would be retained in merchantable timber and not emitted back to the atmosphere. Further, in a forest conservation program, there is also a compensation of the forgone economic benefit of timber that would be logged in the absence of the program (ϕ^c).

$$\Pi_t^{c,cons}\left(a_t^c, w_t^c | p, u^c, X^c, e^c, tran^c, r^c, \omega^c, \phi^c\right) = \tag{9}$$

$$\begin{cases} p\left(s\left(a_t^c|X^c\right) - s\left(a_{t-1}^c|X^c\right) + e^c\right) + b\left(a_t^c|X^c\right) - \left(u^c + \omega^c w_t^c\right)\left(1 + tran^c\right) \; when \; t = 1..T-1 \\ p\left[(1-\gamma)s\left(a_t^c|X^c\right)\right] - \phi^c \; when \; t = 0 \end{cases}$$

The expectation of the net present value generated by the conservation program during its lifespan is represented in eq. (10). The Bellman's recursive form is formalised in eq. (11). The implicit function for the break-even price $p^{c,\,cons}(.)$, the minimum payment that country c would be prepared to receive in the form of a carbon price payment, is represented by eq. (12). There is no closed-form solution for this implicit function, and we must rely on numerical techniques to solve for the break-even price.

$$V_0^{c,cons}\left(a_0^c | p, u^c, X^c, e^c, tran^c, r^c, \omega^c, \phi^c\right) = E_{w^c} \sum_{t=0}^{T} \frac{1}{(1+\rho)^t} \Pi_t^{c,cons} \left(a_t^c, w_t^c | p, u^c, X^c, e^c, tran^c, r^c, \omega^c, \phi^c\right) \tag{10}$$

subject to (7)

$$V_t^{c,cons}\left(a_0^c | p, .\right) = \Pi_t^{c,cons}\left(a_t^c | p, .\right) + \frac{1}{1+\rho} E_{w_t^c} V_{t+1}^{c,cons}\left(a_{t+1}^c | p, .\right) \tag{11}$$

$$V_0^{c,cons}\left(a_0^c | p^{c,cons}(.)\,,.\right) = 0 \tag{12}$$

3. Data and calibration

To quantify the cost factors of forest carbon programs in each country we considered: (i) the carbon density, below- and above-ground, in current forests (ii) the land-use cost; (iii) the GHG emissions with the alternative land use; (iv) the level of governance quality in each country which influences the transaction costs of forest plantation and forest conservation programs; (v) the cost of labour and associated production factors in planting activities; and (vi) fire risks. We combined several global databases and constructed a global dataset to quantify these cost factors across 166 countries.

Data of the country-average forest carbon growth rates is extracted from Cook-Patton et al. (2020: supplementary data). There are a small number of countries where data are not available, and we estimate the carbon density for these countries by taking the average of the density in their border-sharing neighbours, weighted by their average Normalised Difference Vegetation Index (NDVI). The NDVI is calculated from the Moderate Resolution Imaging Spectroradiometer database of NASA (Didan et al., 2015).

The level of fire risk is approximated by data from the FAOSTAT database which provides data about forest land and the burned forest area. We estimated the probability of fire risk by the proportion of burned area over the total forest land, and as the average of 10 years ending 2017. For countries with no or inconsistent data of burned areas (e.g., negative numbers) in FAOSTAT, we estimated the burned area from the Global Fire Emissions Database (Randerson et al., 2018).

Forests are land-intensive (Neudert et al., 2018; Sloan et al., 2018) and their ability to deliver cost-effective climate mitigation is constrained by the increasing human needs for food and fibres (Griscom et al., 2017). In practice, the alternative land use for forests varies, but it is dominated by agriculture (UNFCCC, 2007:p.81; FAO and UNEP, 2020: f.29). Thus, we estimated the cost of land use by the annualised value of agricultural land where the value of agricultural land is taken from Savill's database of the global farmland index. For countries where data are not available, we approximated farmland values by scaling the value-add per hectare of agricultural land where the scale factor is estimated by averaging across countries with available data. The value-add per unit of agricultural land, where needed, was extracted from the World Development Indicators of the World Bank (WDI database).

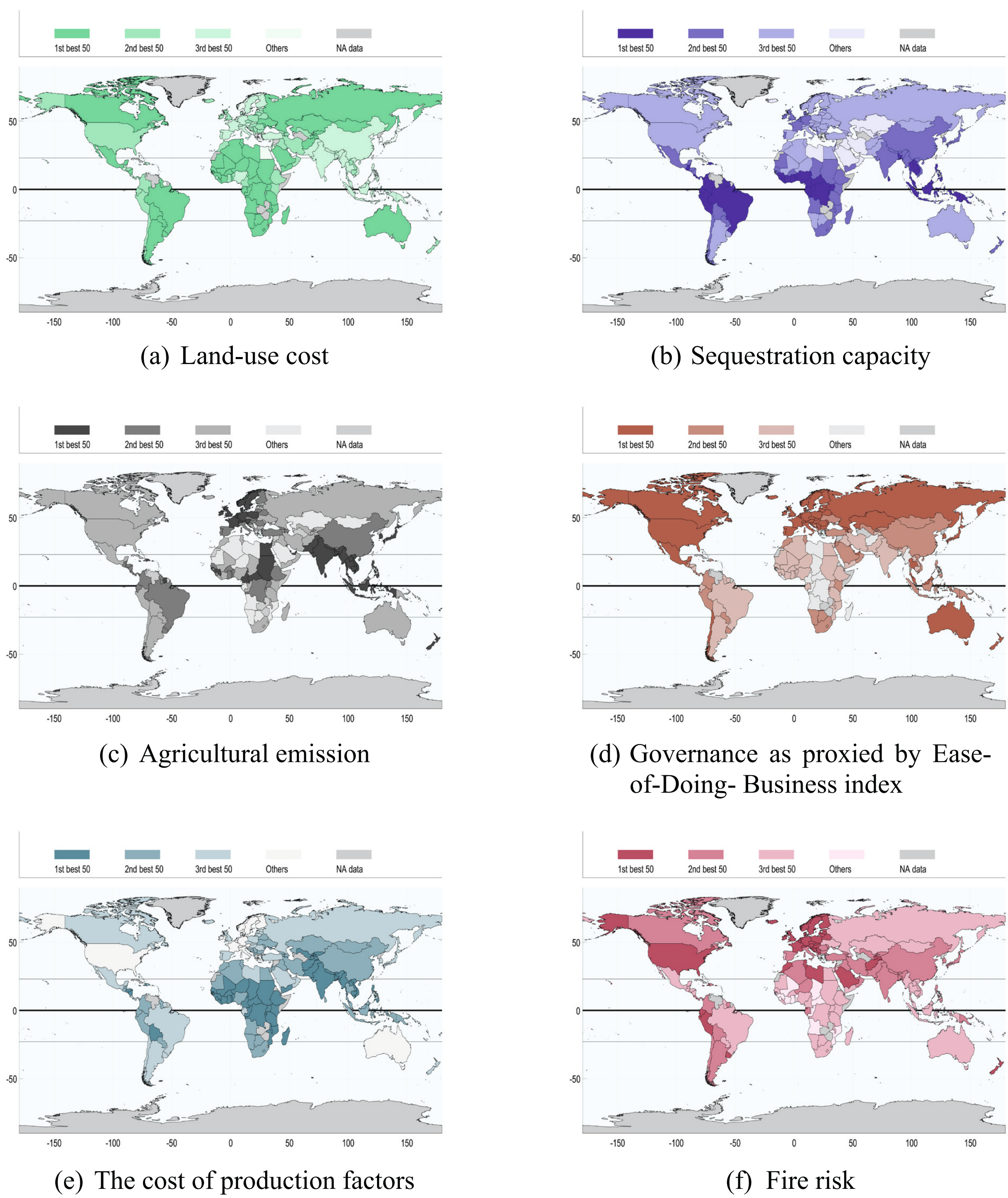
Data for the governance indicator were approximated by the Ease-of-Doing-Business index, extracted from the WDI database of the World Bank. This index is available from 2015 to 2019, and we calculated the average over this period for each country. The average index was used as a proxy for transaction costs. We assumed 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), Fichtner et al. (2003) and Milne (1999) .

The level of GHG emissions for alternative land-use is approximated by the GHG emissions from agricultural activities, which was also extracted from the WDI database. When a program involved planting trees, we assumed the planting cost per hectare was 1-week labour together with other associated production factors (e.g., capital and material). To account for cost uncertainties, we undertook a sensitivity analysis of how our results responded to different parameter values. The value of labour and other production factors is estimated by the total value-add of labour and production factors associated with one employed person. Data for each country were extracted from the WDI database.

To quantify forest co-benefits, we drew from the estimates of forest co-benefits by Costanza et al. (1997) and Costanza et al. (2014). The estimated values of ecological services generated by global forests are, on average, 1338 USD/ha and 3800 USD/ha in 1997 and 2011 (2007-dollar value). We used the 1997 estimates for our low-value scenario, the 2011 estimate for our high-value scenario, and the average of the two for our medium-value scenario.

Forest co-benefits include multiple types of eco-system services. These eco-system services include raw material (e.g., sustainable wood harvest), food production (e.g., integrated cropping), gas regulations, disturbance regulation, water regulation, water supply, erosion control, soil formation, nutrient cycling, waste treatment, pollination, biological control, habitat refugia, genetic resources, recreation, and culture. We classified the eco-system services into two broad groups, namely, market and non-market values following Costanza et al. (2014). Market values include private co-benefits such as raw material services and food production, either as a by-product or integrated farming. These are the values that private stakeholders are likely to account for in their land-use decisions. To control for the difference in local food and material prices, we approximated the market (private) value as a ratio of the agricultural value in each country. The other services were considered non-market (non-private) services, noting that their values vary across countries, and are approximated by average forest quality, as measured by carbon density.

The break-even price of forest carbon programs was estimated with and without the (non-market) non-private value of forest co-benefits. When only the (market) private values were accounted for, we refer to



(a) Land-use cost

(b) Sequestration capacity

(c) Agricultural emission

(d) Governance as proxied by Ease-of-Doing- Business index

(e) The cost of production factors

(f) Fire risk

Fig. 1. Cross-country distribution of cost factors.

this case as the market break-even price for a country-level forest program (plantation or conservation). When non-private values from forest co-benefits were included, our results represent a social break-even price for a country-level forest program (plantation or conservation).

We specified the lifespan of a project to be 70 years in the baseline scenario and varied this parameter in the range of [50,100] in our sensitivity analyses. Tree ages in forest conservation were assumed to be 50 years in the baseline scenario and varied between 40 and 60 years in the sensitivity analyses as the fraction of the merchantable timber varies across types of trees and especially forest age (IPCC, 2006: Table 4.5). In forest conservation, the initial compensation to farmers for not cutting down trees was approximated by the country-specific value of roundtimber per hectare, as extracted from the WDI database. Monetary values are measured in USD, and we used the discount rate of 4.27%, which is the average rate of 30-year US treasury bond between 1998 and 2017 to discount monetary values to 2017-value USD for consistency.

4. Cross-country results

4.1. Cross-country distributions of cost factors

We first analysed the global distribution of the cost factors. Each of these factors was used to classify all countries with available data into four groups, namely, the best (lowest cost) 50 countries, the 2nd best 50, the 3rd best 50, and the remaining countries. The global distribution of the cost factors is plotted in Fig. 1.

The best (lowest-cost) 50 countries in relation to the land-use cost are those with the lowest value of agricultural land. Fig. 1a shows that the land-use cost is lowest in Russia, Central Asia, Australia, most of Africa, Canada, Mexico, and some parts of South America. Many countries in this group are large in size, or lower in population density, or their climate or demographic characteristics make them less suitable for intensive agriculture.

The best (lowest-cost) group in relation to forest quality is, more or less, a different set of countries. As shown in Fig. 1b, South-East Asia and tropical South America are the regions with the highest forest quality. Some tropical African countries, such as Congo, Cameroon, Liberia, and Equatorial Guinea, also perform well in this indicator.

Fig. 1c shows the level of GHG emissions from agriculture across countries. Forest programs in countries that have *higher* GHG emissions from agriculture *avoid* a greater level of carbon emissions, all else equal. The best group includes countries with intensive agricultural activities, such as New Zealand, Japan, South Korea, India and some ASEAN countries; Egypt and the Central African Republic in Africa; the Dominican Republic and Suriname in Central and South America; and several countries in Northern and Western Europe such as Demark, Norway, Sweden, the UK, Germany, Poland, France, Netherland, Ireland, and Italy. We note that, in the absence of an explicit or implicit cost on agricultural GHG emissions, GHG emissions per hectare of agricultural land would not be included in the market price of forest carbon offsets.

Fig. 1d summarises the quality of the business environment. Countries that have the most business-friendly environment are mainly in North America, Europe, North Asia, Australia, and New Zealand. Fig. 1e shows the cross-country comparison of the costs of labour and production factors. We note that the cross-country distribution in Fig. 1e is similar to Fig. 1d, implying that the higher the quality of the business environment is associated with larger labour and production factor costs.

Fig. 1f 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. The data of all cost factors for the 166 countries are provided in the supplementary information section.

The global distribution of individual cost factors in Fig. 1 (a to f) provides an overall picture of the trade-off between the factors that influence the break-even price of forest programs. Ideally, forest-based carbon programs would be most cost-effective in a country that belongs to the best group in relation to all factors. However, we observe that no country is included in the best group for all six categories. For example, countries that have the lowest land-use cost often have an arid or semi-arid climate which is less suitable for forests. This implies there is a trade-off between the cost factors, and this should be accounted for in terms of global-scale carbon sequestration.

4.2. Market break-even price of forest carbon programs

We used the key cost factors in section 4.1 to calculate the market break-even carbon price of forest carbon programs. The calculation of the market break-even price only considers the private (market) value of forest co-benefits (such as the collection of firewood or integrated farming). The market break-even prices are summarised in Table 2 which reports the cross-country comparisons from 150 countries, not including 10% of country outliers. These outliers are small countries in terms of land area, such as the Maldives and Singapore. The high value of land in these outlier countries make them not suitable for a land-intensive industry like forestry.

Table 2 shows that the global average cost of generating forest-based carbon benefit varies with private forest co-benefits and between the two forest programs, plantation and conservation. The table also shows that if forest plantation programs were to be implemented across the 150 countries *at the same scale*, the estimated average cost would be between 19-45USD/tCO_2, depending on the co-benefits. Likewise, if forest conservation were to be implemented at the same scale in all countries, the estimated average cost would be between 10-22USD/tCO_2.

Forest conservation is more cost-effective than plantations for two main reasons. First, forest conservation helps avoid large emissions from existing carbon stock that would happen if deforestation were to occur. Second, forest plantation involves a substantial cost of labour and production factors (capital and material) incurred at the beginning of a plantation program and which has, all else equal, a larger effect on the present value of costs if these costs were incurred later in the plantation program because of discounting.

Table 2 shows that the break-even price of forest carbon varies when projects are targeted to different groups of countries. In particular, the break-even price of forest plantation programs in the top 100 countries is around 11–24 USD/tCO_2, or approximately 60% of the 150-country average. The break-even price of forest conservation programs in the best 100 countries is about 5–12 USD/tCO_2, as compared to 10–22 USD/tCO2 if conservation programs were spread across all 150 countries. Targeting forest programs to the best 50 countries would further reduce the costs of carbon sequestration and reduce the break-even price.

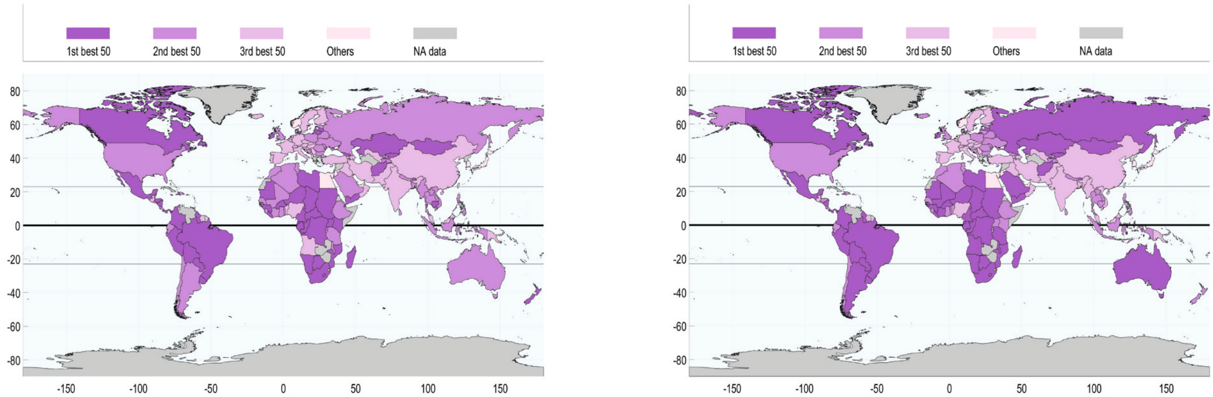
A cross-country distribution of the forest carbon costs is plotted in Fig. 2 for plantation and conservation programs. The market break-even price in this Figure is the average of low, medium, and high value of forest co-benefits. This figure shows that forest-based carbon programs are likely to be more cost-effective (with a lower break-even price) in some countries and regions than others.

For forest plantation, the low-cost countries include Canada, Mexico,

Table 2
Market break-even price of carbon forest programs.

Value of private forest co-benefits	Program category	150 countries*	100 best countries	50 best countries
Low	Plantation	41 [2, 140]	24	14
	Conservation	22 [1, 88]	12	7
Medium	Plantation	31 [1,103]	18	11
	Conservation	16 [1, 65]	9	5
High	Plantation	19 [1, 62]	11	7
	Conservation	10 [0.5, 38]	5	3

Unit: USD/tCO2 (2017-dollar value). Inside the square brackets are the range; *: 10% outliers are excluded.



(a) Forest plantation (b) Forest conservation

Fig. 2. Cross-country distribution of the market break-even price.

and most of Latin America. North Asia where population density is low, some countries in Africa with favorable natural conditions for forests and low labor cost are also among the most cost-effective groups. Surprisingly, most of South-East Asian countries where tropical weather is beneficial for forests, do not belong to the lowest cost group because of either high land-use costs or lower quality of the business environment.

For forest conservation, Canada, Mexico and Latin America are among the lowest-cost group. Some countries in Central Africa, North and Central Asia, as well as Australia in Oceania, are also low-cost locations. South-East Asian countries are not among the lowest-cost countries because of the high cost of land use or the relatively low quality of the business environment. The detailed rankings are provided in the supplementary information.

4.3. Sensitivity analyses

There are three key parameters that influence the results and for which we were not able to find reliable proxy data for all 166 countries. These parameters are: (i) the average lifespan of a forest carbon program, (ii) the average age of existing trees in a conservation program, and (iii) the labor time for planting and associated production factors in planting activities. Thus, we undertook sensitivity analyses to examine how our results respond to each of these parameters.

The sensitivity analyses were undertaken by varying each of these parameters in a range to control for possible uncertainties in their values. We varied the average forest program lifespan from 50 to 100 years, noting that the baseline value is 70 years. The baseline of the average age of existing trees was 60 years in a conservation program, and we varied this parameter in the range [30–90]. The labour time and associated production factors required in planting activities was varied between 0.5 and 1.5 weeks per hectare with the baseline value given at a one week per hectare.

Table 3
Break-even prices with sensitivity analyses (Unit: USD/tCO2–2017 values).

Value of private forest co-benefits	Program category	Project lifespan: 70 years [50–100]	Age of existing tree in conservation projects: 60 years [30–90]	Labour and other production factors in plantation: 1 week/ha [0.5–1.5]
Low	Plantation	41 [36–45]	41 [41–41]	41 [40–42]
	Conservation	22 [21–22]	22 [21−23]	22 [22−22]
Medium	Plantation	31 [27–34]	31 [31–31]	31 [29–32]
	Conservation	16 [15–16]	16 [15–17]	16 [16–16]
High	Plantation	19 [16–21]	19 [19–19]	19 [18–20]
	Conservation	10 [9–10]	10 [9–10]	10 [10−10]

Outside brackets are the results for baseline parameter values of the sampled countries excluding 10% outliers; Inside brackets are corresponding results for minimum and maximum parameter values.

The sensitivity analyses are summarised in Table 3. 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 project lifespan was varied within 30–50% of the baseline value, the average cost of forest carbon changed by only 1–10%. In sum, our results are not sensitive to changes in the age of existing trees in conservation programs, and costs are also insensitive to changes in the labour hours and associated productions factors in plantation activities.

4.4. Improvements in governance and reductions in transaction costs

The distribution of the cost factors in Fig. 1 indicates how the cost-effectiveness of forest carbon programs might be improved. In particular, the cost factor most amenable to change by decision-makers is transaction costs. In the baseline scenario, transaction costs are assumed to be from 10% to 90% of the production cost, equivalent to from 9% to 47% of the total cost, following compatible estimates (Fichtner et al., 2003; Muradian, 2013) and the importance of governance in forest carbon sequestration programs (Helm, 2010; van Kooten, 2017).

Here, we recalculated the cost for each country, assuming that transaction costs vary with governance quality, but they range from 10% to 30% of the production cost. In other words, we assumed that transaction costs could be improved more in countries with low values of the governance index than in countries with high governance quality, but the relative ranking in the business environment remained unchanged.

Table 4 summarises the result of the improvement in transaction

Table 4
Market break-even price of forest carbon with reduction in transaction costs (USD/tCO2–2017 values).

Value of private forest co-benefits	Program category	150 countries average*	100 best countries	50 best countries
Low	Plantation	35 (41)	20 (24)	11 (14)
	Conservation	18 (22)	10 (12)	5 (7)
Medium	Plantation	26 (31)	15 (18)	9 (11)
	Conservation	14 (16)	7 (9)	4 (5)
High	Plantation	16 (19)	9 (11)	6 (7)
	Conservation	8 (10)	4 (5)	3 (3)

Inside the round brackets are the baseline scenario in Table 2.
* : 10% outliers excluded.

costs, together with the baseline numbers inside brackets for comparison. The table shows that reducing transaction costs may reduce forest program costs by around 10–20%. This gain is substantial if we recognise the large scale of global forest programs. For example, if the target were to remove at least 5 billion tCO_2 from the atmosphere per year from 2040 (Anderson and Peters, 2016), and afforestation were the most cost-effective technique for carbon dioxide removal by that time, the gain from the reduced transaction cost alone is between 10 and 15 billion dollars a year (2017 value).

4.5. Social break-even price (inclusion of non-private forest co-benefits) of forest carbon programs

When estimating the cost with non-private co-benefits (e.g., bio-security and water regulation), we further classify forest plantation programs into afforestation and reforestation (or forest improvement) due to the possible difference in non-private benefits. In particular, afforestation is the conversion from other land uses into forest whereas reforestation, in practice, is more about 'increasing' the canopy in a degraded forest or deforested land. For this reason, reforestation should generate more non-private biodiversity co-benefits (FAO, 2015) while afforestation programs may not be as effective at generating co-benefits because they take place on previously non-forested land.

We assumed that reforestation can potentially restore all co-benefits, if the program is of sufficient duration, while afforestation can generate only a fraction of the co-benefits of original forests. This fraction was specified at 15%, 35%, and 58% for the low, medium, and high values of forest co-benefits respectively, corresponding to the ratio between normal and high-quality forests (Costanza et al., 1997; Costanza et al., 2014).

Our results vary with specific scenarios, as shown in Table 5. The range of the 150-country break-even price for a ton of carbon dioxide is [−15,38] USD/tCO_2 for afforestation, [−42, 21] USD/tCO_2 for reforestation, and [−53, 1] USD/tCO_2 for forest conservation. These social break-even prices are lower than the market break-even prices in Table 2, where non-private co-benefits are excluded.

For some countries, after including non-private benefits, the social break-even price may become negative. A negative break-even price implies that forest co-benefits, both private and non-private, exceed the forest production and transaction costs. The substantial difference in the social (with non-private co-benefits) and market (without non-private co-benefit) break-even prices highlights the importance of measuring all benefits from forests and the need for collective action to incentivise forest plantation and forest conservation to maximise social benefits.

Table 5
Break-even prices with non-private co-benefits ($/tCO2–2017 values).

Value of forest co-benefits	Program category	150 countries average*	100 best countries	50 best countries
Low	Afforestation	38 [−1139]	21	11
	Reforestation/ Forest improvement	21 [−31,131]	21	11
	Forest conservation	1 [−25,68]	−10	−16
Medium	Afforestation	17 [−19,97]	4	−5
	Reforestation/ Forest improvement	−9 [−67,84]	4	−5
	Forest conservation	−24 [−49,25]	−33	−39
High	Afforestation	−15 [−59,40]	−26	−35
	Reforestation/ Forest improvement	−42 [−111,18]	−26	−35
	Forest conservation	−53 [−77, −13]	−61	−66

10% outliers excluded. Inside the square brackets are the range.

While the break-even price decreases when non-private co-benefits are considered, there are only minor changes in the ordinal ranking groups across countries. Fig. 3 shows the cross-country distributions in three categories; and they are similar but not identical to the distributions of the market break-even prices for forest plantation and conservation in Fig. 2 where non-private co-benefits are not considered. The ranking of some individual countries varies slightly within each group, but the 1st, 2nd, 3rd best groups remain more or less the same. The detailed ranking is provided in the supplementary information.

5. Sub-national level case studies

In this section, we calibrate our model to sub-national forestry economies in two countries, Australia and Canada. In each country, we estimate the average break-even cost in the states or provinces. The states (or state-level territories) of Australia and the provinces (or provincial-level territories) of Canada are shown in Fig. 4.

In both Australia and Canada, we focus on states and provinces where conditions are relevant for forest industry. They include seven states in Australia (New South Wales, Victoria, South Australia, Western Australia, Northern Territory, Queensland) and 10 provinces in Canada (British Columbia, Alberta, Saskatchewan, Manitoba, Ontario, Quebec, New Brunswick, Nova Scotia, Prince Edward Island, Newfoundland). These locations are not greyed in Fig. 4, and we can find reliable estimate of land-use costs. The greyed states or provinces in Fig. 4 include the Australia Capital Territory (the capital city of Australia is a state-level territory) and the three northern territories in Canada where natural conditions are not, in general, suitable for forest or agricultural production.

In each country, we focus on four key cost-factors which may vary significantly across locations within a country, namely the cost of land use, the average sequestration capacity per hectare of land, the cost of labour and other production factors, and the fire risk. The transaction cost and agricultural emissions are specified at the country-average, and we undertake a sensitivity analysis of how the results in each state or province respond to changes in these two parameters.

5.1. Results for Australia

We summarize the cost factors and the market break-even prices in Australian states in Table 6. Here, the costs of labour and associated production factors, the annualised value of agricultural land, and the break-even price are rounded to the nearest dollar values. As Australia spans from tropical to temperature climate zones with a diversity of natural conditions, some cost factors vary greatly across states. For example, the values of agricultural land are of seventeen-fold difference between the highest and lowest states (i.e., between Tasmania and Northern Territory). The fire risk is of six-fold difference between Northern Territory and South Australia.

The diversity in the cost factors result in a range of the average break-even price of forest-based carbon. In terms of forest plantation, the national-average break-even price is around 30 USD/tCO_2, below the global average, and the price varies from 19 to 64 $/tCO2 across the states. While having the highest land-use opportunity cost, Tasmania has the lower average break-even carbon price among all states because of the relatively lower cost of production, oceanic climate, and lower fire risks. On the other hand, the break-even price is highest in Northern Territory where the land-use cost is minimal, but the cost of production is relatively high, and the fire risk is also higher.

There is also a significant difference between plantation and conservation categories. The average break-even price of carbon in the forest conservation category is only around a quarter of the break-even price in the forest plantation category. The key reason for this difference is that forest plantation involves a cost of labour together with associated capital and material at the plantation stage, and these costs are

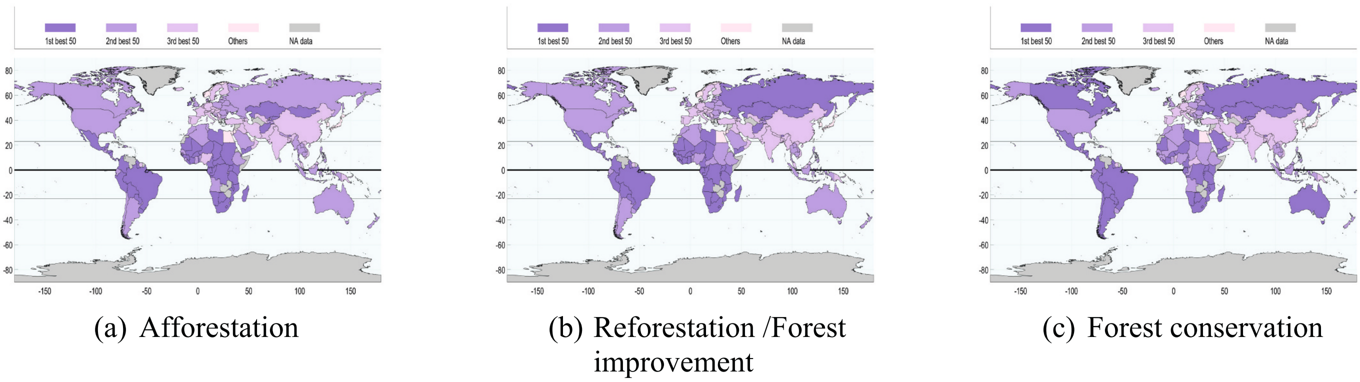


Fig. 3. Cross-country distribution of the average cost with non-private co-benefits.

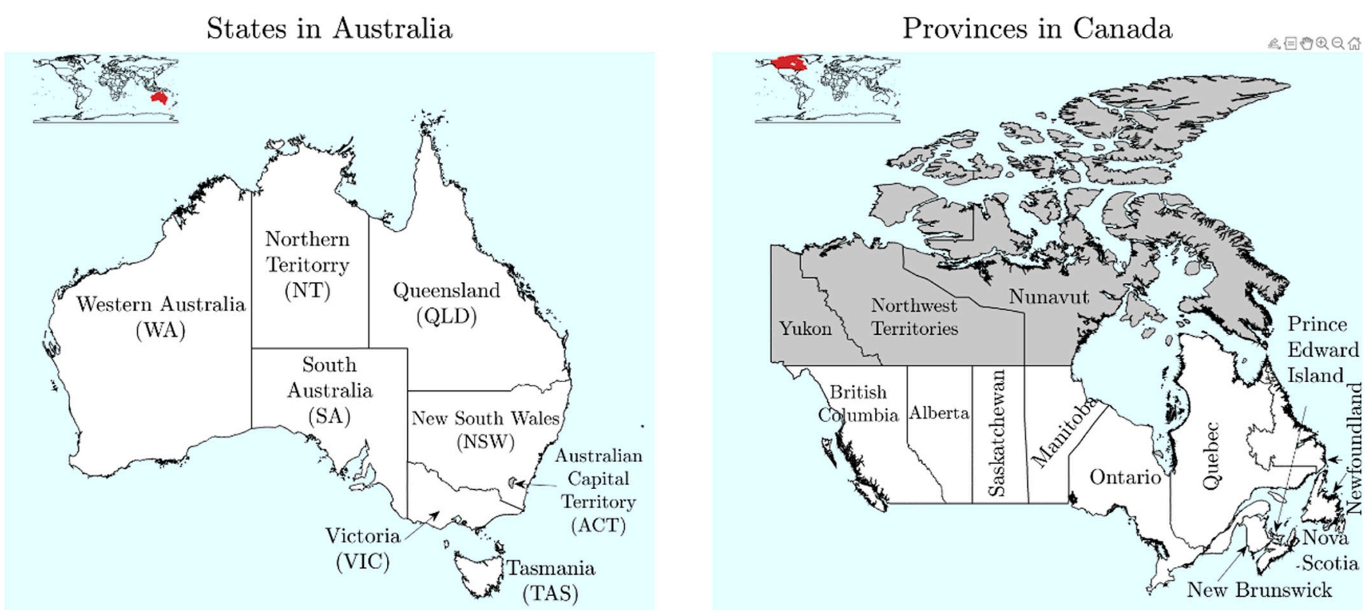


Fig. 4. Australian State and Territories and Canadian Provinces and Territories.

substantial in Australia. The higher cost of labour and production factors in the plantation stage also explains why Tasmania, where this cost is relatively low, has a lower break-even price in forest plantation but is less cost effective in forest conservation than New South Wales and Victoria.

The sensitivity analysis shows that the break-even prices of forest carbon vary with transaction cost and avoided agricultural emissions. Nevertheless, these variations are within 15% of the baseline values even when the transaction cost and the avoided agricultural emissions in each state are varied between 50% and 150% of the national average. These variations are less significant than the variations across the states.

5.2. Results for Canada

The cost factors and the market break-even prices in Canadian provinces are summarised in Table 7. Some cost factors vary significantly across provinces. For example, the land-use opportunity cost in Ontario is nine-fold of that in Saskatchewan, and the production cost of labour (and associated production factors) in Alberta is about double of that in Prince Edward Island. The wildfire risk in most Canadian provinces is relatively small, less than 1% (i.e., less than once per century in each plot of land), except in Manitoba. This is a significant difference between Canada and Australia with the latter experiencing a much higher risk of wildfires.

The average break-even price for carbon in forest plantation category is estimated at approximately 17 USD/tCO_2 in Canada and is in the top (lowest cost) 50 countries, with a cost range between 9 and 36 USD/tCO_2 across provinces. Nova Scotia is the lowest-cost province because of its below-average labour and land-use cost, a much lower risk of wildfires and because of above-average natural conditions (NDVI) for trees. Ontario is the highest-cost province because of the high land-use cost which is more than three-fold of the national average.

The break-even prices also vary across plantation and conservation categories. The break-even price in the conservation category is lower than in the plantation category because forest conservation does not incur the cost of labour and associated production factors in the plantation stage. At the national level, the average break-even price is approximately 5 USD/tCO2, and the price varies between 3 and 9 USD/tCO2 across the provinces in Canada. The sensitivity analysis shows that the break-even prices of forest carbon vary with transaction cost and avoided agricultural emissions, but these variations are also less significant than the variations across provinces.

Our cost estimates assume that economic resources would generate value-adds elsewhere if not used in forestry industries. Agriculture is, typically, a key driver of deforestation such that farmland values can be used as the opportunity cost of land use in forestry. This is a reasonable assumption in many locations, but there are exceptions. We note that the farmland values in British Columbia and Ontario are the highest in

Table 6
Cost factors and market break-even prices in Australian states.

States	The cost of labour and associated production factors ($/ worker/year)	Annualised value of farmland ($/ha/year)	Fire risk	NDVI as a proxy for forest quality	Break-even price ($/tCO2)	
					Plantation	Conservation
New South Wales	118,557	120	0.013	0.6627	21 [19,22], [20,21]	5 [4,5], [5,5]
Queensland	108,378	148	0.037	0.5579	46 [43,50], [43,46]	13 [12,14], [13,14]
Victoria	108,207	189	0.008	0.6470	20 [18,22], [19,20]	5 [5,6], [5,5]
South Australia	104,021	118	0.007	0.4313	27 [24,29], [25,27]	6 [5,6], [6,6]
Tasmania	98,544	306	0.009	0.7517	19 [18,21], [18,19]	6 [6,7], [6,6]
Northern Territory	139,686	18	0.042	0.4492	64 [59,69], [58,64]	15 [14,17], [15,16]
Western Australia	159,773	72	0.029	0.4320	61 [56,67], [56,61]	14 [13,16], [14,15]
National average	117,410	130	0.020	0.5960	30	7

Monetary values are 2017 USD. Break-even prices outside brackets are baseline values. The first bracket pair is sensitivity analysis in each state for 10% and 30% transaction cost (i.e., approximately 50% and 150% of the baseline country-average value). The second bracket pair is sensitivity analysis in each state for agricultural emission between 50% and 150% of the country average.
Data sources:
Cost of labour and agricultural land value: Australian Bureau of Statistics
NDVI: Moderate Resolution Imaging Spectroradiometer database of NASA
Fire probability: Global Fire Emissions Database
Others are estimated by authors.

Canada. However, if existing forest lands are not suitable for agriculture, the average land-use cost of afforestation or deforestation would be lower than the average value of farmland. Thus, the average cost of forest carbon sequestration and storage would also be lower. For example, if the land-use cost of forest programs at a location in British of Columbia were 50$/ha/year, the average cost of carbon would be around only 7.4 USD/tCO_2 in forest plantation and less than 1 USD/tCO_2 in forest conservation.

6. Discussion

We examine the underlying factors of the cost of forest-based carbon programs. We acknowledge that costs may vary in specific projects because of other contextual and variable factors in particular locations. Our estimates are first-order partial-equilibrium approximation noting that there may be cross-sector impacts, e.g., conversion of forest land to agriculture can reduce crop prices and farming profits which in turn reduces the land-use opportunity costs. Our results, with caveats, provide several insights into the costs of forest-based climate mitigation.

First, the average cost of removing carbon from the atmosphere via forests or avoiding emissions from deforestation are substantial in some locations. As the cost of forest carbon varies significantly across countries, locations within countries, and forest program categories, the average cost would rise rapidly when low-cost options are fully explored, consistent with recent estimates at the global scale and in many countries (Vogt-Schilb et al., 2015; Guo and Gong, 2017; Timilsina et al., 2017; Lu et al., 2018; Zhang et al., 2019). Thus, the current carbon price likely underestimates the cost of achieving carbon emission reduction objectives such as the nationally determined contributions towards mitigation of greenhouse gas emissions. Our results highlight the importance of cooperation within a country to explore the lowest-cost national locations and also the need for cross-country cooperation and financial transfers to support carbon sequestration in the lowest cost countries and sub-national regions.

Second, forest programs still remain a cost-effective climate mitigation option. In particular, we observe that our global average estimates for forest-based carbon are less than the estimated cost from alternatives for carbon dioxide removal techniques, such as BECCS and DAC. For example, the cost of BECCS in Sweden could be reduced to 60–75 USD/tCO_2 in ideal circumstances (Garðarsdóttir et al., 2018:t.6), noting that costs are higher in other countries (e.g., Alcalde et al., 2018:f.2; Pour et al., 2018:t.5). DAC, while not a land-intensive carbon dioxide removal technique, has even higher costs, ranging from 94-232USD/tCO_2 (Keith et al., 2018). Other techniques, such as ocean fertilisation and alkalinisation or enhanced weathering are in an early stage of development, and their costs are high (Pires, 2019), and thus, are not considered as viable mitigation options in all climate pathways (IPCC, 2018:p.17).

Third, while forests currently offer a relatively cost-effective mitigation option in some locations, climate change – if not effectively mitigated – will reduce the sequestration capacity of trees and consequently, the cost-effectiveness of forest-based carbon programs. In other words, there is evidence that climate change may diminish growth rates and shorten the time that carbon resides in the eco-system by killing or degrading trees under hot, dry conditions (Sullivan et al., 2020). Consequently, if global temperatures reach a key threshold, dying trees will release warming gases (Pennisi, 2020). In this case, forests may become a less cost-effective mitigation approach.

Fourth, the quality of governance of forest carbon sequestration programs has an important effect on costs at the global scale. Our results show that reducing the transaction costs of forest carbon programs would improve their cost-effectiveness substantially. This finding is consistent with recent research that the cost of climate change abatement is sometimes more sensitive to the governance than to agriculture land price (Gusti et al., 2019). We also observe that some countries that have some of the best natural and economic conditions for forests (i.e., tropical wet weather with low land-use and labour costs) also have

Table 7
Cost factors and market break-even prices in Canadian provinces.

Provinces	The cost of labour and associated production factors ($/ worker/year)	Annualised value of farmland ($/ha/year)	Fire risk	NDVI as a proxy for forest quality	Break-even price ($/tCO2)	
					Plantation	Conservation
British Columbia	87,661	494	0.003	0.603	22 [20,24], [20,24]	9 [8,9], [8,9]
Quebec	79,189	387	0.001	0.556	19 [17,21], [18,21]	7 [7,8], [7,8]
Prince Edward Island	68,281	247	<0.001	0.555	13 [12,14], [12,15]	5 [4,5], [4,5]
Saskatchewan	122,751	81	0.007	0.338	22 [20,24], [19,26]	4 [4,4], [4,5]
Manitoba	85,269	131	0.013	0.410	20 [18,22], [18,24]	6 [5,6], [5,6]
Ontario	91,085	722	0.003	0.523	36 [32,38], [32,40]	16 [14,17], [15,16]
New Brunswick	77,705	181	0.002	0.628	11 [10,11], [10,12]	3 [3,3], [3,3]
Alberta	132,857	182	0.004	0.412	24 [22,26], [21,28]	6 [5,6], [5,6]
Newfoundland	122,531	291	0.003	0.548	21 [19,22], [19,23]	6 [6,7], [6,6]
Nova Scotia	74,630	183	0.001	0.651	9 [9,10], [9,10]	3 [2,3], [3,3]
National average	93,956	203	0.004	0.509	17	5

Monetary values are 2017 USD. Break-even prices outside brackets are baseline values. The first bracket pair is sensitivity analysis in each state for 10% and 30% transaction cost (i.e., approximately 50% and 150% of the baseline country-average value). The second bracket pair is sensitivity analysis in each state for agricultural emission between 50% and 150% of the country average.
Data sources:
Cost of labour and agricultural land value: Statistics Canada
NDVI: Moderate Resolution Imaging Spectroradiometer database of NASA
Fire probability: Global Fire Emissions Database
Others are estimated by authors.

relatively low governance quality as measured by their business environment. Consequently, such countries presently do not represent 'value for money' in relation to forestry carbon sequestration (Africa Development Bank, 2018:p.10,11) in what would otherwise be 'ideal' natural locations for growing trees because of implementation issues, fund mismanagement, and overly complicated administrative processes.

Fifth, where the quality of governance is similar, e.g., across locations within a country, climate may not be the most important cost-factor. This is an important implication for large countries that spans multiple climate zones. Our sub-national case studies in Australia and Canada show that the labour cost of labour and the land-use cost may play a pivotal role, especially in the forest plantation category. For this reason, forest plantation can be more cost-effective in locations with low labour cost and less intensive farming.

Sixth, substantial non-private co-benefits of forest highlights the importance of responding to market failures in climate change mitigation. We find that forest programs in some countries can be shown to have positive net social benefits *if* non-private environmental services are fully considered. The challenge is that non-private co-benefits may not provide adequate incentives for private stakeholders to participate in forest programs. For this reason, financial mechanisms with appropriate principles of conditionality and compliance, e.g., PES, may be needed to achieve the potential of the co-benefits via forest programs (Wunder and Wertz-Kanounnikoff, 2009; Wunder et al., 2018). While promoting non-private ecological services is challenging in both developed and developing countries, that may vary across countries (Poudyal et al., 2016; Keenan et al., 2019), the optimal design of such mechanisms should differ between nations (IPCC, 2018:p.17; Chu et al., 2019).

Finally, our analysis reaffirms the importance of international collaborations in achieving the global target of emission reductions (Keohane and Victor, 2016; Fuso Nerini et al., 2019). Effective mitigation measures require global actions, and global forest resources are not evenly distributed, nor are the costs of carbon sequestration with forests. Importantly, while the impacts of climate change vary across countries (Schiermeier, 2018), practical measures to enhance the co-operation between developed and developing countries, especially to reduce the transaction costs of carbon sequestration, would reduce costs and expand the opportunities for climate change mitigation (Blicharska et al., 2017; Everard et al., 2017; Khan et al., 2020).

7. Conclusions

Using a transparent bottom-up framework based on readily accessible global data sources, we calculate the break-even price to incentivise forestry carbon sequestration using six key cost factors. Our results show large cost differences across countries, across locations within a country, and between categories of forest carbon programs, with and without the inclusion of non-private forest co-benefits. The findings suggest that cost targeting (by locations), in terms of where forest carbon sequestration programs occur, would substantially reduce forest carbon sequestration costs.

We find that forest carbon sequestration programs are cost-effective relative to alternatives but that these costs are sensitive to bio-physical conditions and socio-economic circumstances. We also show find that overall costs of forest carbon sequestration could be reduced with improved project design and better governance. Large cost-reductions from carbon sequestration, at a global scale, are also possible from improved governance and the targeting of forest program to low-cost countries and sub-national regions.

Author statement

Quentin Grafton and Long Chu conceived the research questions. Long Chu and Quentin Grafton devised the methodology and undertook calculations. Long Chu and Hai Nguyen collected the data. Long Chu, Quentin Grafton and Hai Nguyen wrote the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.forpol.2021.102666.

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