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ORIGINAL ARTICLE

Accounting for forest fire risks: global insights for climate change mitigation

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Abstract
Fire is an important risk in global forest loss and contributed 20% to 25% of the global anthropogenic greenhouse gas emissions between 1997 and 2016. Forest fire risks will increase with climate change in some locations, but existing estimates of the costs of using forests for climate mitigation do not yet fully account for these risks or how these risks change inter-temporally. To quantify the importance of forest fire risks, we undertook a global study of individual country fire risks, combining economic datasets and global remote sensing data from 2001 to 2020. Our estimates of forest fire risk premia better account for the risk of forest burning that would be additional to the risk-free and break-even price of credits or offsets to promote carbon sequestration and storage in forests. Our results show the following: (1) forest fire risk premia can be much larger than the historical forest area burned; (2) for some countries, forest fire risk premia have a large impact on the relative country-level break-even price of carbon credits or offsets; (3) a large spatial and inter-temporal heterogeneity of forest fires across countries between 2001 and 2020; and (4) the importance of properly incorporating forest fire risk premia into carbon credits/offset programs. As part of our analysis, and to emphasise the possible sub-national scale differences, our results highlight the heterogeneity in fire risk premia across 10 Canadian provinces.

Keywords Carbon credits · Carbon offsets · Climate change · Land-use change · Forest conservation · CO_2 emissions

Highlights • Forest fire risks are not properly been accounted for in the price of carbon credits or offsets.
• Forest fire risk premia can be multiples of the risk-free carbon credit/offset price and increase exponentially in the frequency of forest fire.
• Forest fire risks have increased in the past two decades in key forested regions of the world.
• Estimates of future forest losses are lower, and estimates of avoided CO_2 emissions are greater, when forest fire risk premia are not properly accounted for in forest carbon storage and sequestration programs.

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1 Introduction

Forests are increasingly being proposed as a low-cost approach to carbon sequestration and storage (Chu et al. 2022) and are supported by several global initiatives. The most recent agreement was the Glasgow Leaders' Declaration on Forest and Land Use (GFA) at the 26th Conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCC) in Glasgow in 2021. This Declaration committed 141 countries to '… halt and reverse forest loss and land degradation by 2030…'. In addition to global agreements, the private and public sectors, and civil society, have developed a series of regulations and incentives to reduce forest loss and associated carbon dioxide emissions. One key financial incentive that has grown in importance over the past two decades is carbon credits and offset programs that pay forest owners to plant trees, to maintain existing forests or to change forest management to store more carbon (e.g. improved forest management); these are cumulatively valued at billions of dollars (Grafton et al. 2021).

To ensure the expected forest area is conserved and avoided carbon dioxide emissions are achieved, the price of carbon credits or offsets must incorporate key risks, including those associated with forest fires, that, along with other human disturbances, reduce the resilience of forests to climate change (Saatchi et al. 2021). Forest fire risks are well studied, likely to be non-stationary, and are affected by climate change (Anderegg et al. 2020; Ellis et al. 2022; Liu et al. 2022; Nelson and Scorah 2021; Senande-Rivera et al. 2022). Nevertheless, forest fire risks have not yet been fully included in the price of carbon credits or offsets despite the increasing use of crediting temporary carbon storage in forests (Galik et al. 2022). Failure to properly account for forest fire risks is of global concern because wildfires are growing in intensity and spreading in range (United Nations Environment Programme 2022). Moreover, the Intergovernmental Panel on Climate Change (IPCC) has observed that the increased frequency of forest fires, as measured by burned areas, is attributed to anthropogenic climate change in important forested regions, including western North America, and with a high degree of confidence (Parmesan et al. 2022).

Where forest fire risks are accounted for in carbon credit/offset programs or in voluntary schemes, this is done with assumptions about the expected area to be lost to fire or other disturbances, as defined by the forested area burned as a percentage of conserved forested land (California Air Resources Board 2014), rather than directly incorporated into the price of carbon credits or offsets (Choi-Schagrin 2021). In the case of California's carbon-offset program, purchasers of credits or offsets for US forest land must include an additional 'buffer' equal to 2% and 4% of the total purchases, respectively, for forest land with and without forest fire reduction programs to ensure a 100-year 'guarantee' on forest carbon claims. An actuarial analysis of California's carbon-offset program indicates that forest wildfires between 2015 and 2021 have already depleted 19% of the buffer over a 7-year period (Badgley et al. 2022); this implies that it is highly unlikely the 100-year forest carbon guarantee will be achieved.

Our key contribution is to provide a method and proof of concept to quantify forest fire risk premia over and above a forest risk-free baseline price for carbon credit/offset programs for 215 countries and territories and at a sub-national level in Canada. Our quantitative framework complements previous studies (e.g. Herteau 2013; Hurteau et al. 2009) with an explicit economic approach to estimating fire risk premia where fire may cause damage at any time during the duration of forest projects. Our estimates of forest fire risk premia are calculated by combining economic and remote sensing data from 2001 to 2020. Without a forest fire risk premium included in a carbon credit/offset price, and where there is a non-zero forest fire risk, the forested area conserved would be less, estimates of avoided carbon dioxide emissions will be greater than expected, and carbon storage and sequestration investments will be distorted.

Our findings are materially important because (1) for some countries, including some that have large forest carbon stocks like Canada, the fire risk premia can be a large proportion of the risk-free and break-even carbon price for carbon sequestration and storage, (2) forest fire risk premia are increasing in some regions of the world, (3) forest fire risk premia are required to both better manage future forest loss and to prioritise where carbon sequestration and storage payments should be targeted, and (4) forest carbon credits or offsets are increasingly being relied on to reduce and to avoid carbon dioxide emissions from the world's forests (Griscom et al. 2017; Harris et al. 2021; Plant for the Planet 2022). In sum, all costs and risks need to be fully priced to ensure the effectiveness of investments in forest-based carbon sequestration.

In Section 2, we detail our methods and model parameterisation. Sections 3 and 4, respectively, include our estimated forest fire risk premia for 215 countries and territories from 2001 to 2020, and at the sub-national level for Canada. In Section 5, we highlight the implications of our findings and offer our conclusions in Section 6.

2 Methods and material

2.1 Forest carbon pricing and fire risk premia

We estimated a forest fire risk premia at a country level and a provincial level in Canada, using a break-even carbon pricing approach used by Chu et al. (2022) and Grafton et al. (2021). This approach calculates the break-even price of carbon offsets or credits for forest plantation and forest conservation programs to ensure ongoing forests and avoid CO_2 emissions. The method considers the benefits and cost of forests, incorporates the opportunity of alternative land use to forests, and parameterises key cost factors: land-use cost, the cost of labour and associated material, average growth rate carbon stock, and avoided emissions from alternative land use.

Our method for calculating a forest fire risk premia uses the subscript c as the country or location index and denotes r^c as the probability of a forest fire in one year in location c. We define T as the duration of the forest plantation or conservation program and w_t^c as a variable which takes the value one if a forest fire occurs at time t, and zero otherwise, as formalised in Eq. (1).

$$w_t^c = \begin{cases} 1 \; with\ probability\ r^c \\ 0 \; with\ probabiity\ 1 - r^c \end{cases} \quad with\ t = 1..T \tag{1}$$

2.1.1 Fire risk premia in forest plantation for carbon sequestration and storage

For forest plantation carbon credit and offset programs, the stochastic dynamics of tree age is specified by Eq. (2) where a_t^c denotes the age of a stand of trees at time t noting that tree age is a random process because trees can be destroyed by a fire and be replanted. 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 trees in a burned area of forest are destroyed, and this generates CO_2 emissions.

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

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

We suppose that a country or location is offered a carbon price p^c for carbon in a forest plantation carbon sequestration and storage program. The break-even price is the carbon credit/offset price that ensures the forest plantation occurs, and the land is not used for its next best land use, which is, typically, agriculture.

The net benefit of the program in year t is formalised in Eq. (3), where the superscript '*plan*' signifies a forest plantation program. In Eq. (3), g^c is the average annual increase in forest carbon stock per unit of land, both above and below ground, and $g^c\left(a_t^c - a_{t-1}^c\right)$ is the change in carbon storage stock between a year and the previous year. The term $\mathbf{1}[X]$ is a function taking the value of 1.0 if the Boolean variable X is true and 0 otherwise, e_t^c is the avoided emission from alternative land use, tr_t^c is the ratio of transaction costs, lu_t^c is land-use cost, and pc_t^c is the cost of planting trees.

$$\Pi_t^{c,plan}\left(p_t^c | e_t^c, g^c, tr_t^c, lu_t^c, pc_t^c, w_t^c\right) = p_t^c\left(e_t^c + g^c\left(a_t^c - a_{t-1}^c\right)\right) - \frac{\left(lu_t^c + pc_t^c \times \mathbf{1}\left[(t = 0) | \left(w_t^c = 1\right)\right]\right)}{1 - tr_t^c} \tag{3}$$

The first term in the RHS of (3) is the carbon benefit, which equals the carbon price times carbon quantity. The carbon quantity includes avoided carbon dioxide emissions from alternative land use and results in a positive change in the carbon stock when there is forest growth or a negative change in carbon stock if a wildfire occurred over that year. The second RHS term of (3) is the cost of forest plantation programs which includes the land-use cost and the plantation cost. A forest plantation cost is incurred at the start of the project and/or after trees are destroyed following a fire.

The net present value (NPV) of continuing a plantation program from time t to the end of a project is calculated via recursive Eq. (4). In this equation, the remaining value of a project at any time includes the expected value of an instantaneous benefit and a future value discounted by an annual rate ρ, noting that a fire may occur with a given probability r^c in any year after forest establishment.

$$\begin{aligned} V^{c,plan}\left(a_t^c, t | p_t^c, r^c\right) = &\left(\tfrac{1}{1+\rho} V^{c,plan}\left(a_t^c + 1, t + 1 | p_{t+1}^c, r^c\right) + \Pi_t^{c,plan}\left(p_t^c | e_t^c, g^c, tr_t^c, lu_t^c, pc_t^c, 0\right)\right) \times (1 - r^c) \\ &+ \left(\tfrac{1}{1+\rho} V^{c,plan}\left(0, t + 1 | p_{t+1}^c, r^c\right) + \Pi_t^{c,plan}\left(p_t^c | e_t^c, g^c, tr_t^c, lu_t^c, pc_t^c, 1\right)\right) \times r^c \end{aligned} \tag{4}$$

The NPV of forest plantation programs depends on the future value of influential factors, including carbon prices, the cost of labour and associated materials, and land-use cost. We use the discount rate ρ to estimate the expected future values of these factors, i.e. $E_0 p_t^c = p_0^c(1 + \rho)^t$, $E_0 pc_t^c = p_0^c(1 + \rho)^t$, and $E_0 lu_t^c = lu_0^c(1 + \rho)^t\left(1 + rg^{lu}\right)^t$ where $E_0(X)$ is the expectation operator given the information at time zero, and rg^{lu} is the real growth rate of land-use cost above general inflation.

We estimated the NPV of plantation programs given the carbon price in the base year 0. The break-even carbon price is equal to a zero expected NPV, as formalised by an implicit function denoted by Eq. (5), where the initial age of trees in a forest plantation program is zero, i.e. $a_0^c = 0$. The fire risk premium is estimated by the difference in percentage points between the carbon price under risk and the risk-free (break-even) price, as specified in Eq. (6).

$$V^{c,plan}\left(0,0|p^{c,plan}(r^c),r^c\right)=0 \tag{5}$$

$$pr^{c,plan}(r^c)=\frac{p^{c,plan}(r^c)}{p^{c,plan}(0)}-1 \tag{6}$$

2.1.2 Fire risk premia in forest conservation programs for carbon sequestration and storage

In forest conservation programs, trees are standing at the commencement of payments associated with carbon credits or offsets. An already standing tree stand means that forest conservation generates an initial carbon benefit in terms of avoiding emissions should the tree be harvested. This initial carbon benefit adds to ongoing carbon benefits throughout the lifespan of a project.

Forest conservation programs do not incur plantation costs unless there is a fire and forest owners choose to replant after the fire. In a forest conservation program, however, there is compensation for the forgone economic benefit of timber that would be harvested without the carbon sequestration or storage program.

The net benefit of a forest conservation program in year t is formalised by Eq. (7), where the superscript '*cons*' signifies forest conservation programs. In this equation, the plantation cost pc_t^c is incurred only when the conservation program continues after a fire ($w_t^c=1$), where nc is the fraction of carbon stocks in non-commercial trees that eventually emit back to the atmosphere when a tree is logged, and ip^c is the forgone economic benefit of timber that would be logged in the absence of the forest conservation program.

The NPV of continuing a forest conservation program from time t is formalised in recursive Eq. (8). The break-even price of a forest conservation program is determined by an implicit function in Eq. (9) which specifies the NPV of the program to be zero, and the fire risk premium is defined by Eq. (10).

$$\begin{aligned}\Pi_t^{c,cons}\left(p_t^c|e_t^c,g^c,tr_t^c,lu_t^c,pc_t^c,ip^c,w_t^c\right)&=p_t^c\left(e_t^c+g^c\left(a_t^c-a_{t-1}^c\right)\right)-\frac{\left(lu_t^c+pc_t^c\times\mathbf{1}\left[\left(w_t^c=1\right)\right]\right)}{1-tr_t^c}\\&+\left(p_0^cg^ca_0^c(1-nc)-\frac{ip^c}{1-tr_t^c}\right)\times\mathbf{1}[(t=0)]\end{aligned} \tag{7}$$

$$\begin{aligned}V^{c,cons}\left(a_t^c,t|p_t^c,r^c\right)&=\left(\frac{1}{1+\rho}V^{c,c,cons}\left(a_t^c+1,t+1|p_{t+1}^c,r^c\right)+\Pi_t^{c,cons}\left(p_t^c|e_t^c,g^c,tr_t^c,lu_t^c,pc_t^c,ip^c,0\right)\right)\times(1-r^c)\\&+\left(\frac{1}{1+\rho}V^{c,plan}\left(0,t+1|p_{t+1}^c,r^c\right)+\Pi_t^{c,cons}\left(p_t^c|e_t^c,g^c,tr_t^c,lu_t^c,pc_t^c,ip^c,1\right)\right)\times r^c\end{aligned} \tag{8}$$

$$V^{c,cons}\left(a_0^c,0|p^{c,cons}(r^c),r^c\right)=0 \tag{9}$$

$$pr^{c,cons}(r^c)=\frac{p^{c,cons}(r^c)}{p^{c,cons}(0)}-1 \tag{10}$$

2.2 Estimating the forest fire risk premia

2.2.1 Fire area burned by country and territory

There are multiple approaches and datasets to estimate fire areas (e.g. Forkel et al. 2019; Hawbaker et al. 2020; Lizundia-Loiola et al. 2020; Otón et al. 2021). For our calibrations, we used the MODIS Burned Area Pixel product (version 5.1) to estimate the fire area burned by country or territory. These data have previously been used to estimate the burn area in multiple locations in the world (see, e.g. Chuvieco et al. 2018; Santana et al. 2020; Wu et al. 2020) and include the monthly burn area at a 0.25×0.25 degree resolution, i.e. 720×1440 pixels on the Earth's surface. Each pixel contains the burn area of each of 18 surface cover types. The 18 surface cover types are listed in Table 3 in the Appendix (the third column), including five tree cover types, types 5 to 9.

We estimated the tree cover area burned in a country or location by summing up the burned area across 12 months and all pixels belonging to that country or location, as specified in Eq. (11). In this equation, $BurnArea^{tree-cover}(c,t)$ is the tree cover area burned in country or location c in year t; $m(t)$ represents the 12 months of year t; and $BurnArea(s,p,m(t))$ is the burn area of surface cover type s at pixel p in month $m(t)$.

$$BurnArea^{tree-cover}(c,t) = \sum_{m(t)\in[1..12]} \sum_{p\in c} \sum_{s=5}^{s=9} BurnArea(s,p,m(t)) \tag{11}$$

2.2.2 Tree cover area and tree cover burn fraction

To approximate the tree cover burn fraction, we first estimated the tree cover area by country or location region in a year. This estimate used the ESA CCI land cover database (ESA 2017) and included annual data of surface-cover types at a $\frac{1}{360} \times \frac{1}{360}$ degree resolution, i.e. $64{,}800 \times 129{,}600$ pixels on the Earth's surface. Each pixel is classified into one of 38 surface cover types in a year. The 38 surface cover types in the land cover database are categorised into 18 groups to be compatible with the 18 surface cover types in the fire burn database, as listed in Table 3 in the Appendix (the fourth column).

We focused on tree cover surface types, i.e. group ID 5–9 in the third column (i.e. $s = 5.9$) or 50 to 90 in the fourth column of Table 3 in the Appendix. The tree cover area in a year was estimated by summing up all pixels that were classified as one of the tree cover types in that year, as in Eq. (12). In Eq. (12), $TreeCover(c,t)$ is the area of tree cover of country or location c in year t and $SurfaceCover(s,p,t)$ is the area of the surface cover type s at pixel p at time t (if any).

$$TreeCover(c,t) = \sum_{s=5}^{s=9} \sum_{p\in c} SurfaceCover(s,p,t) \tag{12}$$

Tree cover burning reduces the tree cover area. To avoid simultaneity in our estimates, when evaluating the scale of tree cover area burned, we estimated the tree cover area burned fraction in a country or location in a year by dividing the fire area burned in that year by the total area for each surface cover type in the *previous* year. This is formalised in Eq. (13), where $BurnFrac^{tree-cover}(c,t)$ is the fraction of the tree cover area burned and represents the likelihood of a current tree cover plot being burned in the following year.

$$BurnFrac^{tree-cover}(c,t) = \frac{BurnArea^{tree-cover}(c,t)}{TreeCover(c,t-1)} \tag{13}$$

The fraction of tree cover area burned in Eq. (13) may be a higher-bound proxy of the wildfire risk. This is because, apart from being ignited by natural reasons, the tree cover burned area can also be caused by human-driven deforestation. Given that the two most significant reasons for deforestation are agricultural expansion and urbanisation (FAO 2020a, 2020b; FAO and UNEP 2020), we considered two additional and lower proxies of the likelihood of tree cover burned area, given by Eqs. (14) and (15).

The proxy in Eq. (14) is calculated by subtracting cropland expansion (if any) of three types of croplands, i.e. surface cover types $s=1$ to $s=3$, from the tree cover burning. In this equation, $LC(s,c,t)$ is the area of surface-cover type s in country/region c in year t. This proxy, denoted as $BurnFrac^{cropland-adjust}$, assumes that all cropland expansion per year is attributed to human-caused tree cover area burned, and it is a lower proxy of tree cover area burned fraction. In Eq. (15), we further subtracted the expansion (if any) of urban areas, i.e. surface cover type $s=19$. The proxy in this equation, denoted as $BurnFrac^{cropland\_urban\_adjust}(c,t)$, assumes that all cropland and urban expansion in a year is attributed to human-ignited tree cover burning.

$$BurnFrac^{cropland\_adjust}(c,t) = \frac{BurnArea^{tree-cover}(c,t) - \max\left(\sum_{s=1}^{s=3} LC(s,c,t) - \sum_{s=1}^{s=3} LC(s,c,t-1), 0\right)}{TreeCover(c,t-1)} \tag{14}$$

$$BurnFrac^{cropland\_urban\_adjust}(c,t) = \frac{BurnArea^{tree-cover}(c,t) - \max\left(\sum_{s=1}^{s=3} LC(s,c,t) - \sum_{s=1}^{s=3} LC(s,c,t-1), 0\right) - \max\left(LC(19,c,t) - LC(19,c,t-1), 0\right)}{TreeCover(c,t-1)} \tag{15}$$

2.3 Data and parameterisation

For many locations, the principal alternative land use for forests is agriculture, which globally accounts for more than 90% of forest land conversion (FAO and UNEP 2020). Thus, we estimated the land use cost of forest programs, assuming that agriculture is the next best alternative land use, and the rent of agricultural land is an opportunity for forested land. We estimated the rent of agricultural land as the residual of all agricultural revenues less costs, including capital and labour, that we interpreted as the share of land in the agricultural value-add.

We estimated the agricultural value-add as the 10-year moving average before the base year 2020 (i.e. $t=0$) because agricultural profits per hectare vary significantly by year. The country-specific shares of land, capital, and labour in agriculture and the agricultural total factor productivity growth rates (a proxy for the real growth rate of agricultural rent) were extracted from IFPRI (2018) and USDA (2020). In addition to using the estimated agricultural value-add to calculate the fire risk premia in each country, we varied this parameter from 50 to 150% of the estimated value to analyse how the risk premia change in response to the agricultural value-add.

Country-specific carbon accumulation rates were extracted from Cook-Patton et al. (2020: supplementary information section). To estimate the non-commercial ratio of trees to the total carbon stock, we combined the average ratio of below-ground carbon stock from IPCC (2006: t4.3-4.4) and the biomass expansion factor from IPCC (2003:t3A.1.10).

Country-specific costs for forest plantation were specified to be a 1-week cost of a working person and associated resources. The cost of a working person and associated resources were estimated via the value-add of the national economy divided by the number of working people, i.e. the total workforce net unemployment. The compensation of foregone revenue of timber in forest conservation programs was estimated by the country-specific value of round wood harvest. These data were extracted from the WDI database of the World Bank.

The digital country boundary to identify whether a pixel belongs to a country was obtained from the World Bank's Official Boundaries database (World Bank 2022). We note that the duration of forest projects varies substantially. For example, plantation and conservation projects can extend to 40, 80, and even 99 years (Pearson et al. 2014; Rizanti et al. 2018; Rohatyn et al. 2023; Stand for trees 2017). In our analysis, we specified the lifespan of a project in a wide range of values, namely 40, 70, and 100 years.

Our baseline fire risk probability was estimated from historical fire burn satellite data with adjustment factors to take into account land management fire (Ward et al. 2018). Previous studies have indicated extensive burning of savannas and agricultural lands in some regions of the world (Magi et al. 2012; Rabin et al. 2015). Thus, we use the estimated fractions of agricultural, pasture, and deforestation fires from the literature to separate wildfire from land management fire. These fractions were estimated at a regional or global scale (Park et al. 2021; Rabin et al. 2015; Rios and Raga 2019), and some countries, such as China, Australia, and India, have specific estimates (Korontzi et al. 2006; Squire et al. 2021; Xie et al. 2016).

We assumed that decisions in relation to forest projects are economically rational; i.e., forest projects are only implemented in locations where historical wildfire frequency is, at most, once every 100 years, given an assumed maximum project lifespan of 100 years. While fire risk may change over time (Anderegg et al. 2022), unfortunately, historical data are insufficient to robustly forecast the future fire risk in all locations. Thus, we varied the fire risk probability from 50 to 150% of the baseline estimate to investigate the sensitivity of fire risk premia to the annual fire risk probability.

All monetary values were converted to USD using the exchange rate extracted from the World Development Indicators database. Future discount and deflator rates were specified to be 4%, comparable to the 30-year bond yield of the US treasury. In our sensitivity analyses, we evaluated other possible values, namely 2% and 6% per annum.

3 Cross-country analyses

3.1 Cross-country assessment of tree cover area burned

Figure 1 summarises a cross-country assessment of the fraction of tree cover area burned, as an estimate of the magnitude in percentage points per year in panel (a) and as an estimate of decadal changes in panel (b).

In magnitude, the fraction of tree cover area burned was highest in tropical Africa. Apart from climatic factors and economic activities, armed conflicts may also explain the very high fraction of tree cover area burned in some of these African countries, e.g. South Sudan (63%), Burkina Faso (46%), Senegal (44%), Chad (40%), and Central Africa

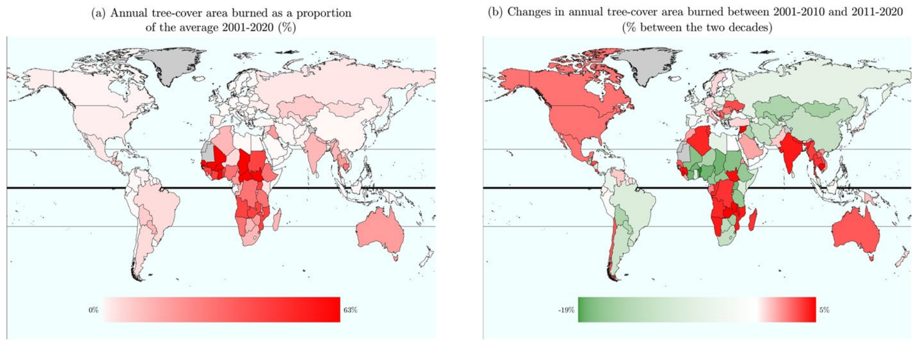

Fig. 1 Cross-country distribution of tree cover area burned

Republic (39%). After Africa, Australia and some countries in South and Southeast Asia also recorded high fractions of tree cover area burned.

Panel (b) of Fig. 1 shows that the changes in tree cover area burned were not uniform across countries. The tree cover area burned declined in some regions, including large countries such as Russia, China, Brazil, and Kazakhstan. These declines contributed to an observed overall reduction in the aggregate tree cover area burned globally. In some countries, however, the tree cover area burned has increased, such as Congo, Zambia, Mozambique, India, Myanmar, Thailand, Laos, Cambodia, and Vietnam. Among high-income countries, Canada, the USA, and Australia recorded the highest increases in the tree cover area burned between the first and the second 10-year periods of this century.

The two panels of Fig. 1 show 'hotspots' in both magnitude and trends of tree cover area burned. In tropical Africa, they include the Congo, Zambia, and Madagascar. In Asia, relative hotspots are India, Myanmar, Thailand, and Cambodia. In Oceania, Australia has the highest magnitude tree cover area burned, with an overall increasing trend over the last 20 years.

Table 1 summarises some descriptive statistics of tree cover area burned fractions (in percentage points) across 215 countries and territories, aggregated into regions. Table 1 reports the median fraction of tree cover area burned, noting that, for comparative purposes, descriptive statistics were calculated separately for the first and the second 10-year periods of this century. On a global scale, the average fraction of tree cover area burned increased in 74 countries/territories, and it declined in 141 other countries/territories, with the median declining from 0.14 to 0.11%.

Many regions of the world had a highly uneven distribution of tree cover area burned such that the highest fraction of tree cover area burned is much larger than the median for the region. This skewed distribution implies that some countries had relatively higher fractions of tree cover area burned than their nearby neighbours, even in the same geographical region. The uneven distributions of tree cover area burned are observed in most regions of the world.

Table 1 further shows that the tree cover area burned increased in several regions of the world; the median fraction of tree cover area burned increased from 0.2 to 0.8% in North Africa and from 1.5 to 1.6% in West Africa. In North America, the tree cover area burned increased from 0.4 to 0.5%, and in Southeast Asia, the tree cover area burned fraction increased in 7 among 12 countries noting that the median only changed slightly. In Oceania, the tree cover area burned increased in both Australia and New Zealand. Other

Table 1 Cross-continental decadal average fraction of tree cover area burned (%), 2001–2020

		Cross-country median of % tree cover area burned [and range]		Decadal changes	
		2001–2010 average	2011–2020 average	Top range/ median	# countries with increases in tree cover area burned
All countries		0.1 [0–62.1]	0.1 [0–64.5]	+/-	74/215
Africa	North Africa	0.2 [0–30]	0.8 [0–24.2]	-/+	3/6
	Middle Africa	16.6 [0–62.1]	14.9 [0–64.5]	+/-	6/10
	East Africa	30.3 [0–51.6]	26.6 [0–47]	-/-	4/15
	West Africa	1.5 [0–35.8]	1.6 [0–38.7]	+/+	7/20
	Southern Africa	5.3 [0–15]	5.0 [0–16.8]	+/-	1/5
America	North America	0.4 [0.3–0.5]	0.5 [0.4–0.6]	+/+	2/2
	Central America	<0.1 [0–1.8]	<0.1 [0–1.7]	-/+	11/31
	South America	0.2 [0–2.8]	0.2 [0–2.4]	-/-	5/14
Asia	Western Asia	<0.1 [0–7.9]	<0.1 [0–7.4]	-/+	5/16
	Central Asia	0.4 [0–1.9]	0.1 [0–1.1]	-/-	0/5
	East Asia	0.4 [0–22.2]	0.1 [0–27.2]	+/-	8/19
	South Asia	0.3 [0.1–4.9]	0.2 [0.1–6.2]	+/-	3/8
	Southeast Asia	0.6 [0–22.2]	0.6 [0–27.2]	+/+	7/12
Europe	Northern Europe	<0.1 [0–0.1]	<0.1 [0–0.1]	-/-	1/13
	Western Europe	<0.1 [0–0]	<0.1 [0–0]	-/+	2/9
	Eastern Europe	0.1 [0–0.9]	0.1 [0–0.9]	-/-	4/10
	Southern Europe	0.2 [0–2.6]	0.3 [0–2.5]	-/+	7/13
Oceania (Australia and New Zealand)		2.9 [0–5.8]	3 [0–6]	+/+	2/2
Other		<0.1 [0–0.2]	<0.1 [0–0.1]	-/+	3/16

Outside brackets are median statistics, and inside brackets are ranges

The Central America group includes the Caribbean region

regions with an increased median tree cover burned area include Central America, the Caribbean, Western Asia, and Southern Europe.

We summarise, in Table 4 in the Appendix, sensitivity analyses after accounting for changes in land use due to increases in cropland and urbanisation in the estimated tree cover area burned fraction. Numerical results changed slightly across scenarios, but the overall trends remain unchanged in most geographical regions. Namely, the risk of tree cover area burned increased in North America (Canada and the USA), Oceania (Australia and New Zealand), and in more than 50% of countries in Southeast Asia. In Southern Asia, the tree cover area burned fraction increased in only three of the eight countries.

3.2 Global distribution of forest cost factors

Figure 2 plots the global distribution of key cost factors that determine the break-even carbon price for carbon credits or offsets. Figure 2a shows that the land-use cost is lowest in Russia, Central Asia, some parts of South America, Australia, and most of Africa. Many countries in this group have a large surface area, a relatively low population density, and/or

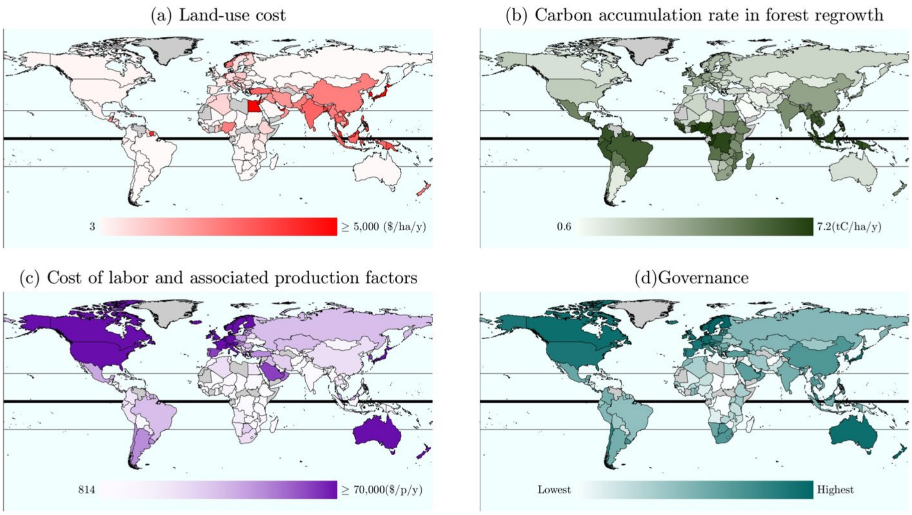

Fig. 2 Cross-country distribution of forest and key cost factors. Notes: (1) Data on carbon accumulation rate in forest regrowth are extracted from Cook-Patton et al. (2020: supplementary information section). (2) Other data are calculated from World Bank World Development Indicators

their climate or demographic characteristics make their parts of their land less suitable for intensive agriculture.

Countries with intensive farming in South Asia, East Asia, and South-East Asia have some of the highest land-use costs. The best (lower cost) group in relation to natural climate conditions for growing forest are shown in Fig. 2b; South-East Asia and tropical South America have the best growing conditions for trees, as well as some tropical African countries, such as Congo, Cameroon, Liberia, and Equatorial Guinea.

Figure 2c and d show the distribution of proxies for the cost of labour and production factors and the quality of governance. These distributions are similar, implying that the cost of labour (or the labour income) is highly correlated with governance. Countries that have the highest labour cost and the most business-friendly environment are mainly in North America and Western Europe, Australia, and New Zealand.

3.3 Fire risk premia

We estimate the fire risk premia for forest plantations and summarise the results of the 100 lowest-cost countries in Fig. 3, with risk-free and full break-even prices for each country reported in Appendix 4 (Table 6). Fire risk premia vary substantially across countries, with some having near-zero estimated risk premia while others have risk premia exceeding 100%. In the latter case, the full break-even price is more than double the risk-free price. Notably, in all scenarios presented in Fig. 3, the median of the risk premia is greater than 9%.

Figure 3 indicates that the duration of forest projects and the severity or probability of forest fires have a greater influence on risk premia than the discount rate and land value. With other factors remaining constant, longer forest projects have a higher probability of being impacted by forest fires, and higher risk severity or probability also leads to an increase in risk premium. We observe that the risk premia, as measured in percentage

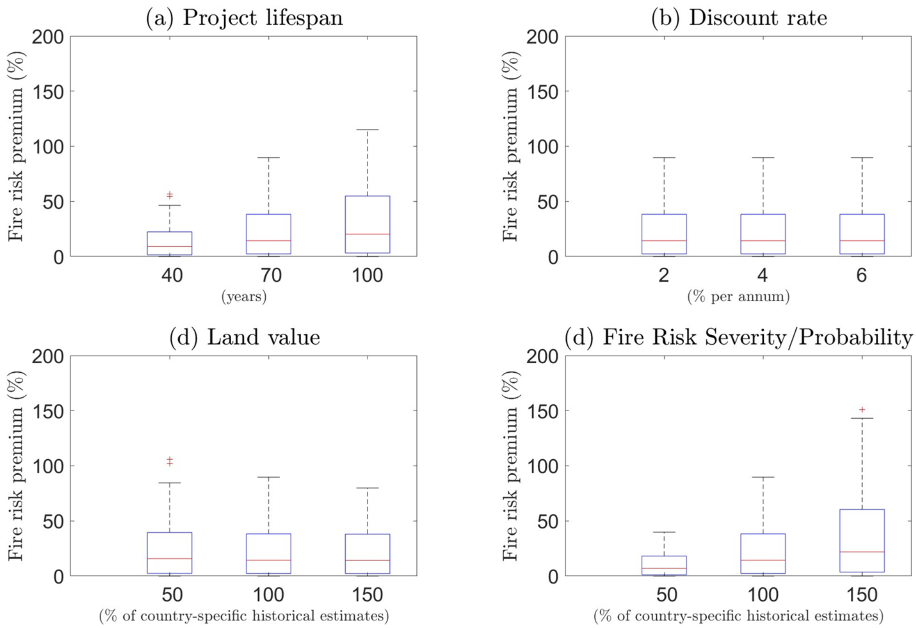

Fig. 3 Sensitivity of fire risk premia for forest carbon plantation in 100 lowest-cost countries

points, are less sensitive to the discount rate and land value. While changes in these economic factors cause both risk-free and full break-even prices to change, the relative difference in percentage points between them remains relatively stable.

The forest fire risk premium increases the break-even carbon credits/offsets because less forest carbon sequestration or storage occurs with forest fires. We observe substantial variation in fire risk premia across countries, which can alter a country's relative cost-effectiveness. For example, while Namibia has a lower risk-free break-even carbon price than Colombia, it has a larger break-even carbon price if a forest fire risk premium is included. Thus, forest fire risk premia play a critical role in the ordinal ranking of countries by their cost-effectiveness for carbon sequestration and, thus, should be used to prioritise the least-cost locations for forest carbon sequestration and carbon storage.

Figure 4 summarises the estimated risk premia in forest conservation programs for the 100 lowest countries, with risk-free and full break-even prices for each country reported in Appendix 5 (Table 7). This figure shows that the fire risk premia in forest conservation vary widely across countries. In some countries, the estimated risk premium is negligible, and there is no difference between the risk-free and full break-even prices. By contrast, in other countries, the risk premium is substantial such that a full break-even price is multiple times greater than the risk-free price.

We find that the risk premia in forest conservation programs increase as the project lifespan lengthens. Longer conservation projects have a higher probability of being impacted by forest fires during their lifespan, assuming a constant risk severity or probability. Thus, a higher risk premium must be incorporated into the carbon price to account for potential losses due to fire risk. This result implies that the risk premium would likely rise with the permanence level of reduced emissions (McCallister et al. 2022).

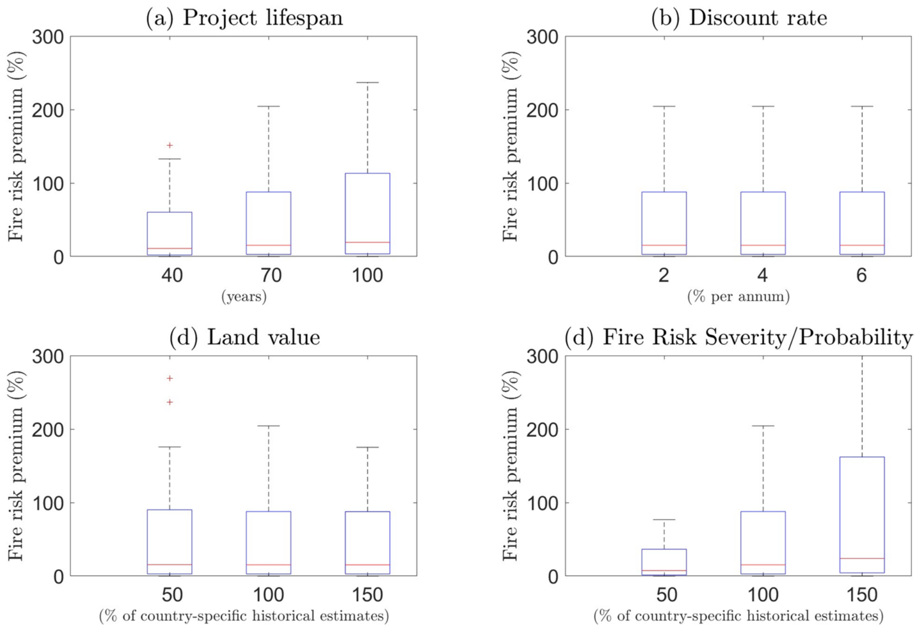

Fig. 4 Sensitivity of fire risk premia for forest conservation in 100 lowest-cost countries

The role of fire risk premia is significant when determining the cost-effectiveness of forest conservation in different countries. Australia, for instance, is ranked 27th in forest conservation with an estimated risk-free break-even carbon price of $US18/tCO2 (see Appendix 5 Table 7). Nevertheless, due to the relatively high risk of fires in Australia, the full break-even price increases to $US42/tCO2 when accounting for the fire risk premium, causing it to fall outside of the top 50 countries with the lowest cost.

Our estimates show that fire risk premia have a more significant impact on the cost-effectiveness of forest conservation than on forest plantation programs. This is explained, in part, by the fact that forest conservation already has standing trees such that a forest fire would increase emissions from the existing carbon stock. By contrast, forest plantation programs initially do not have standing trees, so a forest fire has a smaller (or negligible) impact on carbon dioxide emissions at the beginning of the program.

We highlight that forest plantation and forest conservation programs have different groups of lowest-cost locations, with some overlap. For instance, in approximately 65 of the 100 lowest-cost countries for forest plantation, the estimated break-even price for forest conservation was lower than that for forest plantation. This is due to the substantial differences in the cost of labour and production factors at the plantation stage of forest plantations.

4 Heterogeneity within countries: a sub-national case study

Substantial heterogeneity may exist within countries, especially for countries with large surface areas and a substantial share of global forests, e.g. Canada, the USA, or Brazil. Cost factors may vary in within-country factors such as climate regions, forest types, and sub-national socio-economic conditions. To show how this heterogeneity may manifest itself in different fire risk premia, we calibrated our model to provincial forestry data in Canada, the world's second-largest country by land area with the second-largest number of trees, after Russia. Our data indicate that Canada had an average tree cover area burned fraction of 0.4%/year during the 2001–2020 period (see Appendix 3 Table 5), larger than the median level area burned fraction across 215 countries and territories in our global data (Table 1).

Canada is among the 74 countries or territories where the tree cover area burned has increased over the past 20 years (Fig. 1b). This is consistent with projected trends at the national level (Hanes et al. 2018; Zheng et al. 2023) and in many provinces in Canada (Augustin et al. 2022; Spittlehouse and Dymond 2022). While an increasing national trend in tree cover area burned is expected because of climate change (Gaboriau et al. 2020; Wang et al. 2016; Xu et al. 2022), this trend varies substantially by region and season (Guindon et al. 2021).

Our estimates of forest fire risk premia are provided for each of Canada's 10 provinces: British Columbia, Alberta, Saskatchewan, Manitoba, Ontario, Quebec, New Brunswick, Nova Scotia, Prince Edward Island, and Newfoundland (Fig. 5a). Canada's three northern territories are designated by the greyed areas in Fig. 5a.

Figure 5b–c show that some cost factors vary substantially across provinces, with numerical values reported in Appendix 6 (Table 8). 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. While no tree cover area burned was recorded in Prince Edward Island during the 2001–2020 period, the tree cover burn fraction was over 1.2% in Saskatchewan and 0.53% in Alberta.

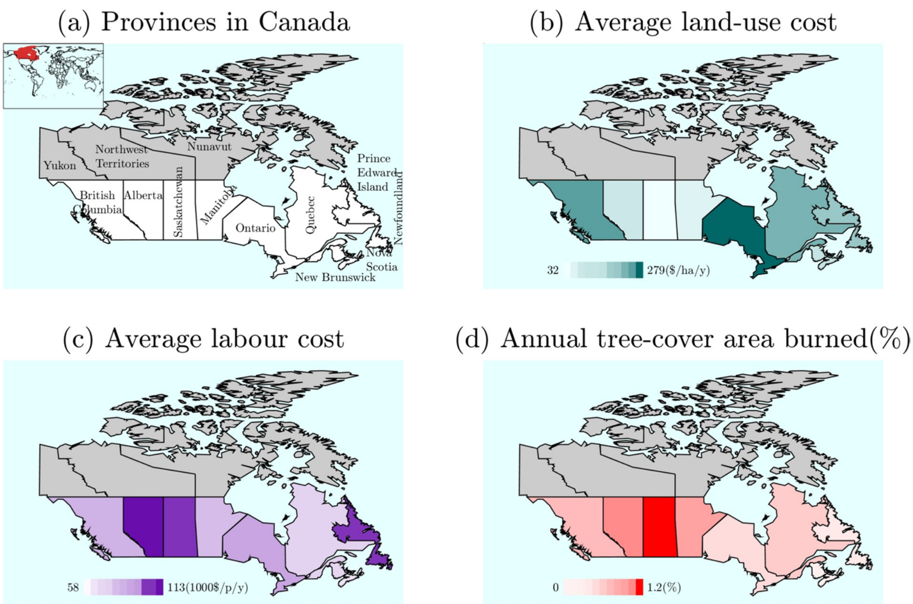

Fig. 5 Provincial distribution of key forest cost factors, Canada

Table 2 Estimated risk-free and break-even carbon prices and forest fire risk premia in Canadian provinces, 2001–2020

Province [estimated fire risk (%/year)]	Risk-free and break-even carbon price (2020 USD/ tCO_2)		Forest fire risk premium (%)	
	Plantation	Conservation	Plantation	Conservation
British Columbia [0.28,0.27,0.26]	56	29	[6,5,5]	[13,12,12]
Quebec [0.19,0.19,0.19]	51	26	[4,4,4]	[9,9,8]
Prince Edward Island [0,0,0]	38	20	[0,0,0]	[0,0,0]
Saskatchewan [1.23,1.23,1.22]	35	9	[44,44,44]	[144,143,143]
Manitoba [0.41,0.4,0.4]	31	12	[11,11,11]	[26,25,25]
Ontario [0.11,0.11,0.1]	89	50	[2,2,2]	[5,5,4]
New Brunswick [0.01,0.01,0.01]	27	12	[0,0,0]	[1,0,0]
Alberta [0.53,0.52,0.5]	45	16	[15,15,14]	[36,35,34]
Newfoundland and Labrador [0.05,0.05,0.05]	47	21	[1,1,1]	[2,2,2]
Nova Scotia [0.01,0,0]	26	12	[0,0,0]	[0,0,0]
National Average [0.36,0.35,0.35]	35	15	[9,9,9]	[20,20,20]

Forest fire risk and associated risk premia are estimated under three scenarios [(i), (ii), (iii)] where (i) tree cover area burned fraction, (ii) tree cover area burn fraction, adjusted for cropland increases, and (iii) tree cover area burned fraction, adjusted for cropland increases and urbanisation

Table 2 summarises the estimates of the risk-free prices and the fire risk premium in Canada's provinces. The break-even prices were relatively higher in forest plantations than in forest conservation in all provinces due to a relatively high cost of labour and production factors in Canada.

The forest fire risk premium was estimated for three scenarios, namely, tree cover area burned fraction, tree cover area burned fraction adjusted with cropland increases, and tree cover area burned fraction adjusted for cropland encroachment and urbanisation. The numerical results in Table 2 show that the estimated risk premium was similar across the estimates of fire risk but varies substantially across provinces and between forest plantation and forest conservation. For forest plantations, the risk premium ranged from 0 in Nova Scotia, where the tree cover area burn was negligible over the 2001–2020 period, to 44% in Saskatchewan, where the fire risk was estimated to be around 1.2% per year. For forest conservation programs, the forest fire risk premia ranged from 0 to 144% of the risk-free break-even carbon credit/offset prices.

The last two columns of Table 2 highlight that the forest fire risk premia may increase in a non-linear way. For example, while the estimated forest fire risk premium in Alberta was around five times that of Ontario, the difference between risk premia for these two provinces is more than seven times. Likewise, the difference in estimated forest fire risk premia between Ontario and Saskatchewan was around ten times, but the difference in fire risk premium was more than 20 times.

Figure 6 shows the sensitivity of forest fire risk premia, using the Canadian national average, to the tree cover area burned and which varies between 0% (Prince Edward Island) and 1.3% (Saskatchewan). Notably, a relatively small tree cover area burned fraction (e.g. 1% per year or around once per century) can result in a large forest fire risk premium with a 30-year project (35% in forest plantation and 110% in forest

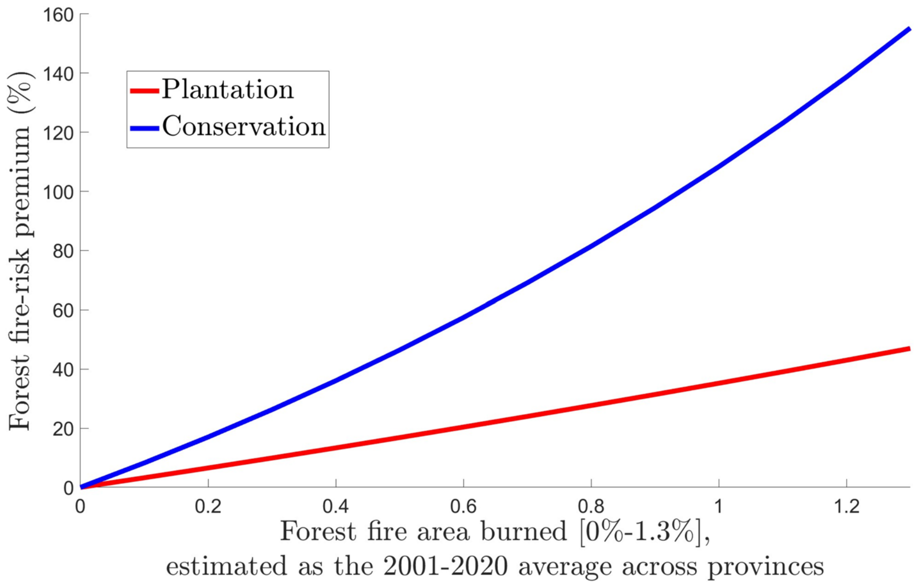

Fig. 6 Forest fire burned area (%) and forest fire risk premia for Canada, 2001–2020

conservation). Furthermore, the forest fire risk premium increases exponentially with each incremental increase in the tree cover area burned fraction.

Figure 6 illustrates that the forest fire risk premium is *not* equivalent to the forest fire area burned (fraction). This is an important finding because the historical frequency of the forest fire area burned is currently used as the proxy for the additional area of forested land to be conserved for carbon sequestration and storage to account for forest fires. We show that the buffer needed to properly account for the forest fire risk premium may be orders of magnitude greater than the historical frequency of the forest fire area burned.

5 Discussion

Fire is a key source of greenhouse gas emissions (van der Werf et al. 2017) and contributes to forest vulnerability (Saatchi et al. 2021) and forest degradation (Silvério et al. 2022; Zhao et al. 2021). Fire also increases the likelihood of irreversible forest loss (Armenteras et al. 2021) and/or reduced tree generation (Rupasinghe and Chow-Fraser 2021; Yadegarnejad et al. 2015). Furthermore, the risk of forest fires imposes higher forest fire suppression costs (Doerr and Santín 2016). These additional costs in terms of forest fire risk must be accounted for in the carbon price of credits or offsets; otherwise, there will be greater than expected net forest losses and larger carbon dioxide emissions than expected or accounted for in forest carbon credits or offsets programs.

Our forest fire risk premium can be incorporated directly into the price of forest carbon credits or offsets or can be used to determine what should be the additional forest area that should be set aside to account for forest fire risk. The presence of fire risks implies that the break-even price of forest carbon will be *higher* compared to situations where there are no such risks. In other words, with a higher break-even price of forest carbon, to achieve the desired quantity of carbon offsets or sequestration, there must be additional forest areas (regulated buffer areas) set aside to account for the potential forest fire risk.

The preferred size of the regulated forest buffer area should be determined using the fire risk premium that we have calculated rather than the frequency of forest fire area burned that is given by the annual risk probability. Importantly, we find that even a small annual risk probability may result in a substantial fire risk premium such that the forest risk premium can be more than double the risk-free price. That is, setting aside an additional 1% buffer area for forest projects is insufficient to account for a wildfire risk that occurs once every 100 years. As shown in Fig. 6 for Canada's ten provinces, the forest fire risk premium buffer can be much larger than the historical frequency of the forest fire area burned. The forest fire risk premia we calculate also indicate that existing regulated buffers in carbon credit or offset programs to account for wildfires should be much larger. Thus, our results have a material impact on what should be the buffer in existing forest carbon credits or offset programs.

Using satellite data, we found that the forest area burned at a global scale has declined over the past two decades, but this trend hides large differences across regions (Bountzouklis et al. 2022; Jolly et al. 2015). Notably, forest fire risks have increased in some locations (e.g. Canadell et al. 2021; Hanes et al. 2018; Kukavskaya et al. 2016), and this trend is expected to continue with climate change (Doerr and Santín 2016; Krikken et al. 2021; Wu et al. 2021). We found that in much of Africa, South Asia, North America, and Oceania, there is an increasing trend in the forest area burned. Improvements in the precision and accuracy of our estimates may be possible with higher-resolution data and better algorithms (Hawbaker et al. 2020; Lizundia-Loiola et al. 2020; Otón et al. 2021; Wei et al. 2021), especially when distinguishing between natural and human-ignited fires.

Forest conservation (or avoided deforestation) is, in general, more cost-effective than forest plantations in terms of avoiding or reducing carbon dioxide emissions, especially in locations where tree plantation costs are relatively high. Nevertheless, our cross-country assessment and the Canadian sub-national analysis show that the cost-effectiveness of forest conservation can be more affected by the inclusion of a forest fire risk premium than forest plantations. In some countries, the inclusion of a forest fire risk premium can change the lowest cost option, switching from forest conservation to forest plantation, such as in the case of Brazil, noting there will be large sub-national differences for large countries. Importantly, because forest fires result in additional carbon dioxide emissions, mitigating their size and frequency reduces CO_2 emissions (Arora and Melton 2018) and improves the cost-effectiveness of forest-based climate change mitigation.

Nearly 40% of global forest loss was associated with fire between 2003 and 2018 (van Wees et al. 2021), and these fires could be naturally ignited, e.g. by lightning, or by anthropogenic influence (Coogan et al. 2020; Kirchmeier-Young et al. 2017). Technical solutions (e.g. Girardin and Terrier 2015) and integrated knowledge systems that account for fire risk would assist in managing fire risk (Johnston et al. 2020). In addition, as our results show, forest owners, managers, and regulators need a transparent method to calculate forest fire risk premia. These forest fire risk premia, in turn, can be used to (1) prioritise where investments in forest conservation should occur, globally and sub-nationally and (2) assist in allocating resources for fire suppression spatially and over time, as fire risk premia change.

We highlight that wildfire is just one of climate change's disturbance risks to forests. Other factors can have large carbon impacts, such as droughts, biotic agents like insects, and storms (Anderegg et al. 2015; Hartmann et al. 2022; MacLean 2016; Michaelian et al. 2011; Robbins et al. 2022). Furthermore, forest offsets must consider other important aspects such as changes in albedo, net cooling (e.g. Bala et al. 2007; Betts 2000), additionality, and leakages (Roopsind et al. 2019; West et al. 2020). Such factors must also be accounted for and costed within forest programs intended to sequester or store carbon.

6 Conclusions

Many national governments are committed to reducing forest losses to reduce the growth in atmospheric carbon dioxide concentrations. Multiple approaches are being used to reduce forest losses, including incentives to plant trees and maintain existing forests. Given there is an economic incentive in many locations, especially in tropical forests, to transform forest land into alternative land use (e.g., agriculture), regulations, and/or financial incentives are necessary to prevent further forest loss.

An increasingly popular tool to avoid carbon dioxide emissions from forests is carbon credits or offsets that provide payments to forest owners to plant trees and/or conserve existing forests. Under existing carbon credits or offsets, forest fire risks are not properly incorporated into the price of forest carbon credits or offsets. When existing carbon credit or offset programs do account for forest fires, this is implemented as a required buffer or set aside based on the historical frequency of tree cover area burned rather than as a forest fire risk premium.

Our results show that the current approach to account for wildfires underestimates the expected forest fire risk or, equivalently, estimates a larger volume of avoided carbon dioxide emissions than what would be expected to occur with forest fires. This poses an immediate challenge to the integrity of carbon credit or offset programs and undermines existing global commitments to reduce forest losses. If forests are to effectively contribute to climate change mitigation targets, either with public or private investments, such financial incentives must be not only cost-effective but also credible. This is especially important when forest fire risks are increasing due to climate change, and it requires that all carbon credit or offset programs properly account for wildfire and other risks (e.g. droughts, biotic agents such as insects, and storms).

Using satellite data over the period 2001–2020 and with a transparent break-even carbon pricing model, we estimated the forest fire risk premia of 215 regions and territories in the world. These forest fire risk premia generate important insights about how to better manage and incentivise forest owners to reduce net forest losses and global carbon dioxide emissions. In particular, we found the following: (1) the buffer or set-aside areas to account for forest fire risks in many existing carbon credits or offset programs is inadequate; (2) a large spatial and intertemporal heterogeneity of forest fire risks globally; (3) an increasing trend in forest fire premia in several countries, including Canada and the USA, that have large forest carbon stocks; and (4) substantial changes in the least-cost ranking of locations for forest carbon sequestration and storage after including a forest fire risk premia to the risk-free, break-even carbon credit or offset price.

Appendix

Table 3 Land cover type

#	CCI description of land cover	Land cover index in fire burn database	Land cover
1	No data	0	0
2	Cropland rainfed	1	10
3	Cropland rainfed herbaceous cover	1	11
4	Cropland rainfed tree or shrub cover	1	12
5	Cropland irrigated	2	20
6	Mosaic cropland	3	30
7	Mosaic natural vegetation	4	40
8	Tree broadleaved evergreen closed to open	5	50
9	Tree broadleaved deciduous closed to open	6	60
10	Tree broadleaved deciduous closed	6	61
11	Tree broadleaved deciduous open	6	62
12	Tree needle leaved evergreen closed to open	7	70
13	Tree needle leaved evergreen closed	7	71
14	Tree needle leaved evergreen open	7	72
15	Tree needle leaved deciduous closed to open	8	80
16	Tree needle leaved deciduous closed	8	81
17	Tree needle leaved deciduous open	8	82
18	Tree mixed	9	90
19	Mosaic tree and shrub	10	100
20	Mosaic herbaceous	11	110
21	Shrubland	12	120
22	Shrubland evergreen	12	121
23	Shrubland deciduous	12	122
24	Grassland	13	130
25	Lichens and mosses	14	140
26	Sparse vegetation	15	150
27	Sparse tree	15	151
28	Sparse shrub	15	152
29	Sparse herbaceous	15	153
30	Tree cover flooded fresh or brackish water	16	160
31	Tree cover flooded saline water	17	170
32	Shrub or herbaceous cover flooded	18	180
33	Urban	19	190
34	Bare areas	20	200
35	Bare areas consolidated	20	201
36	Bare areas unconsolidated	20	202
37	Water	21	210
38	Snow and ice	22	220

Table 4 Tree cover burn adjusted with cropland increase and urbanisation

		Tree cover only		Subtracting increases in cropland from tree cover burn		Subtracting increases in cropland and urbanisation from tree cover burn	
		Changes in top/median	# countries with increases in burn	Changes in top/median	# countries with increases in burn	Changes in top/median	# countries with increases burn
All countries		+/-	74/215	+/-	90/215	+/-	87/215
Africa	Northern Africa	-/+	3/6	-/+	3/6	-/+	4/6
	Middle Africa	+/-	6/10	+/-	6/10	+/-	6/10
	Eastern Africa	-/-	4/15	+/-	5/15	+/-	4/15
	Western Africa	+/+	7/20	+/+	8/20	+/+	7/20
	Southern Africa	+/-	1/5	+/-	2/5	+/-	2/5
America	Northern America	+/+	2/2	+/+	2/2	+/+	2/2
	Central America	-/+	11/31	-/+	11/31	-/-	11/31
	Southern America	-/-	5/14	-/-	8/14	-/-	7/14
Asia	Western Asia	-/+	5/16	+/+	7/16	+/+	6/16
	Central Asia	-/-	0/5	-/-	2/5	-/-	2/5
	Eastern Asia	+/-	8/19	+/-	8/19	+/-	8/19
	Southern Asia	+/-	3/8	+/+	7/8	+/+	6/8
	South-East Asia	+/+	7/12	+/+	6/12	+/+	6/12
Europe	Northern Europe	-/-	1/13	-/+	4/13	-/+	4/13
	Western Europe	-/+	2/9	-/+	2/9	-/+	2/9
	Eastern Europe	-/-	4/10	-/-	3/10	-/-	3/10
	Southern Europe	-/+	7/13	+/+	9/13	+/-	9/13
Australia and New Zealand		+/+	2/2	+/+	1/2	+/+	2/2
Others		-/+	3/16	-/+	2/16	-/+	2/16

The Central America group includes the Caribbean region

Table 5 Tree cover area burned fraction by countries/territories

#	Name	Tree cover area burned (%)			Tree cover area burned, cropland-adjusted (%)			Tree cover area burned, cropland and urbanisation-adjusted (%)		
		2001–2020	2001–2010	2011–2020	2001–2020	2001–2010	2011–2020	2001–2020	2001–2010	2011–2020
1	Afghanistan	0.3	0.3	0.2	0.1	0.1	0.2	<0.1	<0.1	<0.1
2	Albania	0.8	0.8	0.8	0.8	0.8	0.8	0.7	0.7	0.7
3	Algeria	4.6	4.1	5	2.6	1	4.3	2.1	0.7	3.6
4	American Samoa	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
5	Andorra	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
6	Angola	37	36	38	37	36	37	37	36	37
7	Anguilla	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
8	Antigua & Barbuda	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
9	Argentina	1.2	1.3	1.1	1	0.8	1.1	0.9	0.8	1
10	Armenia	0.8	0.9	0.6	0.7	0.9	0.5	0.5	0.6	0.3
11	Australia	5.9	5.8	6	5.8	5.6	5.9	5.8	5.6	5.9
12	Austria	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
13	Azerbaijan	0.5	0.5	0.5	0.4	0.3	0.5	0.2	0.2	0.2
14	Bahamas	1.1	1	1.2	1.1	1	1.2	1.1	0.9	1.2
15	Bahrain	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
16	Bangladesh	0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
17	Barbados	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
18	Belarus	0.3	0.3	0.2	0.3	0.3	0.2	0.2	0.2	0.2
19	Belgium	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
20	Belize	0.6	0.6	0.7	0.6	0.6	0.6	0.6	0.5	0.6
21	Benin	31	41	22	31	40	21	31	40	21
22	Bhutan	0.1	0.1	<0.1	0.1	0.1	<0.1	0.1	0.1	<0.1
23	Bolivia	1.7	2.2	1.3	1.7	2.1	1.3	1.7	2.1	1.2
24	Bosnia & Herzegovina	0.2	0.2	0.3	0.2	0.2	0.2	0.2	0.2	0.2
25	Botswana	4.8	4.9	4.6	4.5	4.4	4.6	4.4	4.4	4.5
26	Brazil	1	1.1	1	0.9	0.9	1	0.9	0.9	1

Table 5 (continued)

#	Name	Tree cover area burned (%)			Tree cover area burned, cropland-adjusted (%)			Tree cover area burned, cropland and urbanisation-adjusted (%)		
		2001–2020	2001–2010	2011–2020	2001–2020	2001–2010	2011–2020	2001–2020	2001–2010	2011–2020
27	British Indian Ocean Territory	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
28	British Virgin Islands	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
29	Brunei Darussalam	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
30	Bulgaria	0.1	0.2	<0.1	0.1	0.2	<0.1	<0.1	0.1	<0.1
31	Burkina Faso	46	52	41	42	44	41	42	44	40
32	Burundi	14	17	12	14	16	12	14	16	11
33	Cote d’Ivoire	26	29	23	26	29	23	26	29	23
34	Cambodia	25	22	27	24	21	27	24	21	27
35	Cameroon	13	15	11	13	15	11	13	15	11
36	Canada	0.4	0.3	0.4	0.4	0.3	0.4	0.3	0.3	0.4
37	Cape Verde	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
38	Cayman Islands	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
39	Central Africa	40	42	37	39	42	37	39	42	37
40	Chad	40	45	35	39	44	34	39	44	34
41	Chile	0.3	0.2	0.3	0.2	0.2	0.3	0.2	0.2	0.3
42	China	0.3	0.4	0.1	0.3	0.4	0.1	<0.1	0.1	<0.1
43	Christmas Island	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
44	Colombia	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1
45	Comoros	0.8	1.1	0.6	0.8	1.1	0.5	0.7	1	0.4
46	Congo	3.9	3.3	4.5	3.9	3.3	4.4	3.9	3.3	4.4
47	Cook Islands	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
48	Costa Rica	0.6	0.5	0.7	0.6	0.5	0.7	0.5	0.4	0.7
49	Croatia	0.1	<0.1	0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
50	Cuba	0.7	0.8	0.5	0.6	0.7	0.5	0.6	0.7	0.5

Table 5 (continued)

#	Name	Tree cover area burned (%)			Tree cover area burned, cropland-adjusted (%)			Tree cover area burned, cropland and urbanisation-adjusted (%)		
		2001–2020	2001–2010	2011–2020	2001–2020	2001–2010	2011–2020	2001–2020	2001–2010	2011–2020
51	Cyprus	<0.1	<0.1	0.2	<0.1	<0.1	0.2	<0.1	<0.1	0.2
52	Czech Republic	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
53	Korea, DPR	0.7	0.8	0.5	0.5	0.7	0.4	0.5	0.7	0.3
54	Congo, DR	19	18	19	18	18	19	18	18	19
55	Denmark	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
56	Djibouti	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
57	Dominica	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
58	Dominican	0.2	0.2	0.1	0.2	0.2	0.1	<0.1	0.1	<0.1
59	Ecuador	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
60	Egypt	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
61	El Salvador	1.5	1.3	1.7	1.5	1.3	1.7	1.4	1.3	1.6
62	Equatorial Guinea	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
63	Eritrea	0.3	0.3	0.3	0.2	0.1	0.3	<0.1	0.1	<0.1
64	Estonia	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
65	Ethiopia	25	27	23	25	27	23	25	27	23
66	Falkland Islands (Malvinas)	0.1	0.3	<0.1	0.1	0.3	<0.1	0.1	0.3	<0.1
67	Faroe Islands	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
68	Fiji	0.2	0.2	0.1	0.1	0.2	<0.1	0.1	0.2	<0.1
69	Finland	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
70	France	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
71	French Guiana	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
72	French Polynesia	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
73	French Southern and Antarctic Territories	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
74	Gabon	0.2	0.2	0.3	0.2	0.2	0.3	0.2	0.2	0.3

Table 5 (continued)

#	Name	Tree cover area burned (%)			Tree cover area burned, cropland-adjusted (%)			Tree cover area burned, cropland and urbanisation-adjusted (%)		
		2001–2020	2001–2010	2011–2020	2001–2020	2001–2010	2011–2020	2001–2020	2001–2010	2011–2020
75	Gambia	40	42	37	39	42	37	39	42	36
76	Georgia	0.2	0.3	0.2	0.2	0.3	0.1	0.2	0.2	0.1
77	Germany	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
78	Ghana	47	47	47	47	47	47	47	47	47
79	Gibraltar	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
80	Greece	0.2	0.2	0.1	0.2	0.2	0.1	0.1	0.1	<0.1
81	Grenada	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
82	Guadeloupe	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
83	Guam	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
84	Guatemala	1.6	1.8	1.3	1.5	1.7	1.3	1.5	1.7	1.3
85	Guinea	31	30	32	31	30	32	31	30	32
86	Guinea-Bissau	25	25	25	25	25	24	25	25	24
87	Guyana	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
88	Haiti	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
89	Honduras	1.6	1.4	1.7	1.6	1.4	1.7	1.5	1.4	1.7
90	Hong Kong	0.2	0.4	<0.1	0.2	0.4	<0.1	<0.1	0.1	<0.1
91	Hungary	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
92	Iceland	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
93	India	5.5	4.9	6.2	5.5	4.9	6.2	5.3	4.6	5.9
94	Indonesia	0.2	0.2	0.2	0.1	0.2	0.1	0.1	0.1	0.1
95	Iran (Islamic Republic of)	0.2	0.3	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
96	Iraq	7.7	7.9	7.4	3.5	0.8	6.3	<0.1	<0.1	<0.1
97	Ireland	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
98	Isle of Man	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1

Table 5 (continued)

#	Name	Tree cover area burned (%)			Tree cover area burned, cropland-adjusted (%)			Tree cover area burned, cropland and urbanisation-adjusted (%)		
		2001–2020	2001–2010	2011–2020	2001–2020	2001–2010	2011–2020	2001–2020	2001–2010	2011–2020
99	Israel	<0.1	0.1	<0.1	<0.1	0.1	<0.1	<0.1	<0.1	<0.1
100	Italy	<0.1	<0.1	0.1	<0.1	<0.1	0.1	<0.1	<0.1	<0.1
101	Jamaica	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
102	Japan	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
103	Jordan	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
104	Kazakhstan	1.4	1.8	1.1	0.6	0.7	0.4	0.5	0.6	0.4
105	Kenya	1	1	0.9	0.8	0.7	0.9	0.7	0.6	0.8
106	Kyrgyzstan	0.3	0.4	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
107	Lao	1.3	1.2	1.4	1.2	1	1.3	1.2	1	1.3
108	Latvia	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
109	Lebanon	0.7	0.6	0.7	0.5	0.4	0.6	<0.1	<0.1	0.1
110	Lesotho	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
111	Liberia	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
112	Libyan Arab Jamahiriya	0.1	0.1	<0.1	0.1	0.1	<0.1	<0.1	<0.1	<0.1
113	Liechtenstein	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
114	Lithuania	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
115	Luxembourg	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
116	Madagascar	4.4	4	4.8	4.4	3.9	4.8	4.4	3.9	4.8
117	Malawi	15	13	16	14	13	16	14	13	15
118	Malaysia	<0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
119	Mali	37	40	35	36	38	34	36	38	34
120	Martinique	<0.1	0.2	<0.1	<0.1	0.2	<0.1	<0.1	0.2	<0.1
121	Mauritius	<0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
122	Mayotte	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1

Table 5 (continued)

#	Name	Tree cover area burned (%)			Tree cover area burned, cropland-adjusted (%)			Tree cover area burned, cropland and urbanisation-adjusted (%)		
		2001–2020	2001–2010	2011–2020	2001–2020	2001–2010	2011–2020	2001–2020	2001–2010	2011–2020
123	Mexico	1	1	1.1	1	0.9	1.1	0.9	0.8	1
124	Micronesia	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
125	Moldova	0.3	0.3	0.4	0.3	0.3	0.4	0.2	0.1	0.3
126	Monaco	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
127	Mongolia	1.4	2	0.8	1.2	1.8	0.7	1.2	1.8	0.7
128	Montenegro	0.6	0.3	1	0.6	0.3	0.9	0.6	0.3	0.9
129	Montserrat	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
130	Morocco	0.2	0.2	0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
131	Mozambique	26	25	27	26	25	27	26	25	27
132	Myanmar	4.5	4.4	4.7	4.5	4.2	4.7	4.5	4.2	4.7
133	Namibia	16	15	17	15	14	17	15	14	17
134	Nepal	3.3	2.5	4	3.2	2.5	4	3.2	2.5	4
135	Netherlands	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
136	Netherlands Antilles	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
137	New Caledonia	<0.1	<0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
138	New Zealand	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
139	Nicaragua	0.8	0.9	0.8	0.8	0.9	0.8	0.8	0.9	0.8
140	Niger	1	1.4	0.7	0.3	0.5	<0.1	<0.1	<0.1	<0.1
141	Nigeria	19	23	15	18	22	15	18	21	15
142	Niue	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
143	Norfolk Island	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
144	Northern Mariana Islands	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
145	Norway	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
146	Oman	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1

Table 5 (continued)

#	Name	Tree cover area burned (%)			Tree cover area burned, cropland-adjusted (%)			Tree cover area burned, cropland and urbanisation-adjusted (%)		
		2001–2020	2001–2010	2011–2020	2001–2020	2001–2010	2011–2020	2001–2020	2001–2010	2011–2020
147	Pakistan	0.4	0.4	0.4	0.2	<0.1	0.4	<0.1	<0.1	0.2
148	Palau	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
149	Panama	0.1	0.1	<0.1	0.1	0.1	<0.1	<0.1	0.1	<0.1
150	PNG	0.1	<0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
151	Paraguay	2.6	2.8	2.4	2.4	2.5	2.3	2.4	2.4	2.3
152	Peru	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
153	Philippines	0.1	0.1	0.1	0.1	0.1	<0.1	<0.1	<0.1	<0.1
154	Poland	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
155	Portugal	2.5	2.6	2.5	2.5	2.4	2.5	2.1	2	2.2
156	Puerto Rico	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
157	Qatar	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
158	Republic of Korea	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
159	Reunion	0.2	0.2	0.2	0.2	0.2	0.2	0.1	<0.1	0.1
160	Romania	<0.1	<0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
161	Russian	0.9	0.9	0.9	0.9	0.9	0.8	0.9	0.9	0.8
162	Rwanda	2	1.8	2.3	2	1.6	2.3	1.6	1.3	1.9
163	Saint Kitts and Nevis	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
164	Saint Lucia	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
165	Saint Vincent and the Grenadines	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
166	Samoa	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
167	Sao Tome and Principe	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
168	Saudi Arabia	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
169	Senegal	45	45	45	45	45	45	45	45	45
170	Serbia	0.2	0.2	0.3	0.2	0.2	0.3	0.2	<0.1	0.2

Table 5 (continued)

#	Name	Tree cover area burned (%)			Tree cover area burned, cropland-adjusted (%)			Tree cover area burned, cropland and urbanisation-adjusted (%)		
		2001–2020	2001–2010	2011–2020	2001–2020	2001–2010	2011–2020	2001–2020	2001–2010	2011–2020
171	Seychelles	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
172	Sierra Leone	24	21	27	24	21	27	24	21	27
173	Singapore	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
174	Slovakia	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
175	Slovenia	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
176	Solomon Islands	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
177	Somalia	<0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
178	South Africa	5.1	5.3	5	4.8	4.8	4.8	4.3	4.5	4.1
179	South Sudan	63	62	65	63	62	65	63	62	65
180	Spain	0.3	0.3	0.3	0.3	0.3	0.3	0.1	<0.1	0.2
181	Sri Lanka	0.1	0.2	0.1	<0.1	<0.1	0.1	<0.1	<0.1	<0.1
182	Sudan	27	30	24	26	29	24	26	28	24
183	Suriname	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
184	Svalbard and Jan Mayen Islands	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
185	Swaziland	6.9	7.6	6.2	6.5	6.7	6.2	6.4	6.7	6.1
186	Sweden	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
187	Switzerland	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
188	Syrian Arab Republic	1.3	<0.1	2.5	1	<0.1	2	0.2	<0.1	0.4
189	Taiwan	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
190	Tajikistan	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
191	Thailand	6.2	5.8	6.6	6.2	5.8	6.6	6	5.6	6.4
192	Macedonia	0.4	0.3	0.4	0.3	0.3	0.4	0.3	0.2	0.4
193	Timor-Leste	1.8	2	1.6	1.7	1.9	1.5	1.7	1.9	1.5
194	Togo	30	33	27	30	33	27	30	33	27

Table 5 (continued)

#	Name	Tree cover area burned (%)			Tree cover area burned, cropland-adjusted (%)			Tree cover area burned, cropland and urbanisation-adjusted (%)		
		2001–2020	2001–2010	2011–2020	2001–2020	2001–2010	2011–2020	2001–2020	2001–2010	2011–2020
195	Tonga	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
196	Trinidad and Tobago	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
197	Tunisia	0.8	0.3	1.4	0.4	<0.1	0.7	0.2	<0.1	0.3
198	Turkey	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
199	Turkmenistan	0.2	0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
200	Turks and Caicos Islands	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
201	UK	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
202	Uganda	29	32	25	29	32	25	29	32	25
203	Ukraine	0.5	0.4	0.7	0.5	0.4	0.6	0.4	0.2	0.6
204	United Arab Emirates	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
205	Tanzania	23	25	22	23	25	22	23	25	22
206	USA	0.5	0.5	0.6	0.5	0.5	0.5	0.4	0.3	0.5
207	United States Virgin Islands	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
208	Uruguay	0.3	0.4	0.2	0.3	0.3	0.2	0.2	0.3	0.1
209	Uzbekistan	1.2	1.9	0.4	1.1	1.9	0.2	<0.1	<0.1	<0.1
210	Vanuatu	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
211	Venezuela	0.4	0.3	0.4	0.3	0.3	0.4	0.3	0.3	0.3
212	Vietnam	0.9	0.9	1	0.9	0.8	1	0.7	0.7	0.8
213	Yemen	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
214	Zambia	37	36	39	37	36	39	37	36	39
215	Zimbabwe	11	12	10	11	12	10	11	12	10

Table 6 Break-even carbon price for forest plantation in the lowest-cost 100 countries

#	Country name	Risk-free price ($/tCO2)	Full price ($/tCO2)	Estimated risk premium
1	Afghanistan	21.1	22.7	8%
2	Angola	12.2	17.4	42%
3	Argentina	13.2	20.3	53%
4	Australia	27.8	46.0	66%
5	Austria	54.3	54.4	0%
6	Belarus	18.5	19.9	7%
7	Belgium	40.8	40.9	0%
8	Belize	46.5	53.5	15%
9	Benin	32.1	44.7	39%
10	Bhutan	42.5	43.9	3%
11	Bolivia	1.9	2.9	51%
12	Bosnia and Herzegovina	41.6	44.8	8%
13	Botswana	2.4	4.4	86%
14	Brazil	5.2	7.4	44%
15	Bulgaria	46.5	48.4	4%
16	Burkina Faso	13.7	18.7	36%
17	Burundi	26.4	36.4	38%
18	Cambodia	46.9	62.2	33%
19	Cameroon	22.1	30.8	39%
20	Canada	33.0	37.5	14%
21	Chad	13.1	17.7	36%
22	Chile	13.1	14.4	10%
23	Colombia	4.7	5.0	7%
24	Congo, Dem. Rep.	11.5	16.1	40%
25	Congo, Rep.	2.7	3.9	47%
26	Costa Rica	59.9	68.1	14%
27	Croatia	81.0	83.8	3%
28	Denmark	30.6	30.7	0%
29	Djibouti	4.0	4.0	0%
30	Dominican Republic	54.6	56.5	3%
31	Ecuador	20.6	21.1	3%
32	El Salvador	49.8	67.6	36%
33	Estonia	18.1	18.2	0%
34	Ethiopia	38.7	51.1	32%
35	Fiji	54.9	58.2	6%
36	Finland	58.4	58.4	0%
37	France	37.1	37.6	1%
38	Gambia, The	37.9	50.9	34%
39	Germany	41.4	41.5	0%
40	Ghana	27.8	39.2	41%
41	Greece	43.4	45.8	5%
42	Guinea	5.7	8.0	40%
43	Guinea-Bissau	44.8	60.0	34%
44	Guyana	26.8	27.2	2%

Table 6 (continued)

#	Country name	Risk-free price ($/tCO2)	Full price ($/tCO2)	Estimated risk premium
45	Haiti	65.9	66.9	1%
46	Honduras	38.8	52.7	36%
47	Iceland	31.9	31.9	0%
48	Ireland	12.2	12.5	3%
49	Jamaica	66.5	67.7	2%
50	Kazakhstan	4.8	9.2	90%
51	Kenya	32.1	42.9	34%
52	Kyrgyz Republic	17.8	19.3	8%
53	Lao PDR	58.7	77.6	32%
54	Latvia	15.3	15.5	1%
55	Lesotho	5.3	5.3	0%
56	Liberia	30.5	31.2	2%
57	Lithuania	15.5	15.8	2%
58	Luxembourg	29.3	29.3	0%
59	Madagascar	6.0	8.1	35%
60	Malawi	25.7	35.3	38%
61	Mali	21.0	28.5	36%
62	Mexico	20.6	26.5	29%
63	Moldova	21.6	24.0	11%
64	Mongolia	3.2	5.4	69%
65	Mozambique	6.8	9.5	41%
66	Namibia	3.6	6.0	65%
67	New Zealand	76.0	76.1	0%
68	Nicaragua	20.3	24.3	20%
69	Niger	14.7	20.0	36%
70	Nigeria	52.3	73.2	40%
71	North Macedonia	73.9	82.1	11%
72	Panama	23.9	24.6	3%
73	Paraguay	5.0	7.2	45%
74	Peru	7.2	7.3	1%
75	Poland	67.4	67.9	1%
76	Portugal	31.0	42.2	36%
77	Romania	66.4	68.2	3%
78	Russian Federation	11.9	16.9	42%
79	Rwanda	44.8	54.7	22%
80	Samoa	84.2	84.2	0%
81	Saudi Arabia	69.4	70.1	1%
82	Senegal	22.1	30.3	37%
83	Serbia	69.8	74.4	7%
84	Sierra Leone	32.1	44.7	39%
85	South Africa	7.3	11.0	50%
86	Spain	42.9	47.6	11%
87	Sudan	18.2	25.1	38%
88	Sweden	63.8	64.0	0%

Table 6 (continued)

#	Country name	Risk-free price ($/tCO2)	Full price ($/tCO2)	Estimated risk premium
89	Switzerland	76.1	76.1	0%
90	Tajikistan	55.4	55.6	0%
91	Tanzania	25.5	34.6	36%
92	Togo	14.5	20.4	40%
93	Uganda	27.4	37.4	37%
94	Ukraine	12.4	14.6	18%
95	UK	24.2	24.8	2%
96	USA	33.3	40.8	22%
97	Uruguay	8.5	9.4	11%
98	Vanuatu	42.8	44.4	4%
99	Zambia	5.5	7.7	39%
100	Zimbabwe	14.6	20.3	39%

Table 7 Break-even carbon price for forest conservation in the lowest-cost 100 countries

#	Country name	Risk-free price ($/tCO2)	Full price ($/tCO2)	Estimated risk premium
1	Afghanistan	28.4	32.8	15%
2	Angola	9.6	19.2	100%
3	Argentina	12.0	24.4	104%
4	Australia	17.7	42.1	138%
5	Austria	49.0	49.1	0%
6	Belarus	22.8	26.0	14%
7	Belgium	41.0	41.2	0%
8	Belize	36.7	48.0	31%
9	Benin	28.0	54.5	95%
10	Bhutan	35.5	37.8	6%
11	Bolivia	1.5	3.2	112%
12	Bosnia and Herzegovina	39.2	45.2	15%
13	Botswana	1.3	3.8	185%
14	Brazil	4.8	9.3	95%
15	Bulgaria	42.5	45.8	8%
16	Burkina Faso	17.6	32.9	87%
17	Cambodia	38.3	68.3	78%
18	Cameroon	19.2	37.5	95%
19	Canada	22.6	28.2	25%
20	Chad	16.9	31.0	84%
21	Chile	18.1	21.3	18%
22	Colombia	3.8	4.3	13%
23	Congo, Dem. Rep.	10.6	20.9	97%
24	Congo, Rep.	2.7	5.6	106%
25	Costa Rica	59.1	75.4	28%
26	Croatia	73.7	78.6	7%
27	Czech Republic	86.2	86.7	1%
28	Denmark	29.2	29.3	0%
29	Dominican Republic	44.6	47.6	7%
30	Ecuador	17.3	18.1	5%
31	Estonia	22.7	22.8	1%
32	Fiji	45.0	50.3	12%
33	Finland	48.4	48.5	0%
34	France	32.3	33.1	2%
35	Gambia, The	40.3	73.5	82%
36	Georgia	74.1	84.0	13%
37	Germany	41.3	41.3	0%
38	Ghana	35.5	70.6	99%
39	Greece	33.9	37.3	10%
40	Guinea	9.4	18.4	95%
41	Guinea-Bissau	41.3	74.8	81%
42	Guyana	21.5	22.1	3%
43	Haiti	65.2	66.9	3%
44	Honduras	33.5	62.0	85%

Table 7 (continued)

#	Country name	Risk-free price ($/tCO2)	Full price ($/tCO2)	Estimated risk premium
45	Hungary	80.2	82.5	3%
46	Iceland	18.6	18.6	0%
47	Indonesia	70.1	74.8	7%
48	Ireland	10.9	11.4	4%
49	Italy	71.9	75.7	5%
50	Jamaica	54.8	56.7	3%
51	Kazakhstan	2.5	7.5	204%
52	Kyrgyz Republic	14.0	16.2	15%
53	Lao PDR	48.3	85.3	77%
54	Latvia	21.5	21.9	2%
55	Liberia	26.5	27.6	4%
56	Lithuania	20.0	20.6	3%
57	Luxembourg	25.0	25.0	0%
58	Madagascar	9.4	17.0	81%
59	Malawi	30.9	58.9	91%
60	Mali	22.5	41.8	85%
61	Mexico	17.1	27.5	61%
62	Moldova	27.2	33.0	21%
63	Mongolia	2.2	5.3	143%
64	Mozambique	7.2	14.4	99%
65	Namibia	3.4	7.6	126%
66	Netherlands	87.9	88.4	1%
67	New Zealand	68.9	69.1	0%
68	Nicaragua	18.1	25.7	42%
69	North Macedonia	61.2	74.9	22%
70	Panama	18.8	19.8	5%
71	Paraguay	5.2	10.1	95%
72	Peru	5.6	5.8	2%
73	Poland	66.9	67.8	1%
74	Portugal	32.2	57.5	79%
75	Romania	61.7	64.8	5%
76	Russian Federation	9.0	16.8	86%
77	Samoa	67.9	67.9	0%
78	Saudi Arabia	48.9	49.8	2%
79	Senegal	20.7	39.1	89%
80	Serbia	65.0	73.5	13%
81	Sierra Leone	30.9	60.4	96%
82	Slovak Republic	91.4	92.9	2%
83	Slovenia	77.6	77.8	0%
84	South Africa	19.6	39.4	101%
85	Spain	34.8	42.2	21%
86	Sri Lanka	80.8	87.3	8%
87	Sudan	18.1	34.6	91%
88	Sweden	52.8	53.1	1%

Table 7 (continued)

#	Country name	Risk-free price ($/tCO2)	Full price ($/tCO2)	Estimated risk premium
89	Switzerland	64.6	64.7	0%
90	Tajikistan	72.4	73.0	1%
91	Tanzania	22.5	41.6	85%
92	Togo	21.3	42.1	98%
93	Trinidad and Tobago	88.2	90.3	2%
94	Ukraine	15.9	21.5	35%
95	UK	20.9	21.8	4%
96	USA	24.1	33.7	40%
97	Uruguay	59.6	69.0	16%
98	Vanuatu	34.5	37.1	7%
99	Zambia	6.7	12.7	91%
100	Zimbabwe	15.3	29.3	91%

Table 8 Cost factors in Canadian provinces

#	Province	Average land use cost ($/ha/y)	Average cost of labour and production factors ($/p/y)	Tree cover area burned fraction	Tree cover area burned fraction, cropland adjusted	Tree cover area burned fraction, cropland and urbanisation adjusted
1	British Columbia	186	74	0.28%	0.27%	0.26%
2	Quebec	155	67	0.19%	0.19%	0.19%
3	Prince Edward Island	113	58	0%	0%	0%
4	Saskatchewan	32	104	1.23%	1.23%	1.22%
5	Manitoba	50	72	0.41%	0.4%	0.4%
6	Ontario	279	77	0.11%	0.11%	0.1%
7	New Brunswick	76	66	0.01%	0.01%	0.01%
8	Alberta	70	113	0.53%	0.52%	0.5%
9	Newfoundland and Labrador	120	104	0.05%	0.05%	0.05%
10	Nova Scotia	76	63	0.01%	0%	0%
11	National Average	79	80	0.36%	0.3%	0.41%

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Data availability The data that support the findings of this study are available from (i) the European Space Agency (MODIS Burned Area Pixel product version 5.1 and Land Cover CCI product version 2.02017), (ii) the International Food Policy Research Institute (Agricultural Total Factor Productivity (TFP): 2018 Global Food Policy Report Annex Table 5), (iii) the United State Department of Agriculture (the International Agricultural Productivity dataset), and (iv) the World Bank (the World Development Indicators database). Collated data for each country is available from the authors upon reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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