A Supply Curve for Forest-Based CO_2 Removal

Sergio L. Franklin Jr. Robert S. Pindyck*

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Abstract: Forestation is viewed as a way to remove CO_2 from the atmosphere and thereby reduce net CO_2 emissions. But how much CO_2 can be removed, and at what cost? Focusing on forested and forestable areas in South America, and using spatially disaggregated data, we estimate a supply curve for forest-based atmospheric CO_2 removal. The supply curve traces out the marginal cost of removing a metric ton of CO_2 as a function of total annual CO_2 removal. Each point on the curve corresponds to a specific location, and accounts for land opportunity, tree planting, and maintenance costs. We show that over a billion tons of CO_2 can be removed annually via forestation at a cost below $45 per ton, and about 2.5 billion tons can be removed at a cost below $90 per ton. The supply curve applies to South America, but with sufficient data could be extended to the entire world.

JEL Classification Numbers: Q5, Q57, C6

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*Franklin: Superintendência de Seguros Privados, Av. Presidente Vargas 730, Rio de janeiro, RJ 20071-900, Brazil; sergio.franklin@insead.edu. Pindyck: Sloan School of Management, MIT, Cambridge, Mass., USA; rpindyck@mit.edu. Our thanks to Gustavo Fonseca, Rachel Garret, Marina Hirota, Robert Mendelsohn, Carlos Nobre, Richard Schmalensee, and participants at various seminars for helpful comments and suggestions. The authors declare that they have no relevant or material financial interests that are related to the research described in this paper.

Global CO_2 emissions continue to rise. That may eventually change, but even with a substantial decline in emissions, the atmospheric CO_2 concentration will keep growing and remain high for many years. That is why policy objectives often focus on *net* emissions, and the need to remove CO_2 from the atmosphere. But how? Planting trees (afforestation and reforestation) is seen as a promising solution, but where and at what cost? Here we focus on forested and forestable land in South America, and use spatially disaggregated data to estimate a supply curve for forest-based atmospheric CO_2 removal. The supply curve traces out the marginal cost of removing a metric ton of CO_2 as a function of total annual CO_2 removal. Each point on the curve corresponds to a specific location, so our analysis tells us where and how many trees can be planted, and at what cost.[1]

Before explaining our methodology, here are some very rough numbers to help set the stage for our work:

1. Estimates vary depending on climate, the age and type of tree, and the local tree density, but on average a mature (about 10 to 20 years old) hardwood tree will absorb about 20 kg of CO_2 per year.

2. Again, the numbers vary considerably depending on climate and type of tree, but on average at least 500 trees can be grown and maintained on one hectare of land.[2]

3. How much land could potentially be forested? Using satellite data, one recent study puts the global number of hectares that could be forested at about 1 billion. If we take this number at face value, full forestation of all available land could remove about $1 \times 10^9 \times 500 \times .02 = 10$ Gt (billion tons) of CO_2 per year from the atmosphere.[3]

4. Global CO_2 emissions are currently around 40 Gt per year. Thus, we could potentially reduce net emissions by about 25% by foresting all 1 billion hectares. That won't bring the world to net zero, but 25% is a good start.

So why aren't we planting large numbers of trees? We are indeed planting some trees, but cutting down many more. As shown in Figure 1, during the period 2015 to 2020, there were

[1] Considerable ongoing R&D is focused on carbon removal and sequestration (CRS) technologies, but those technologies are currently too expensive for practical use. See Pindyck (2022) and references therein. Other land- and water-based plants, such as mangroves and kelp, can also absorb CO_2, but compared to trees, their absorption potential is limited.

[2] 1 hectare = .01 square kilometers $\approx$ 2.47 acres.

[3] This estimate of 1 billion hectares is by Bastin et al. (2019). Also see references in Pindyck (2022).

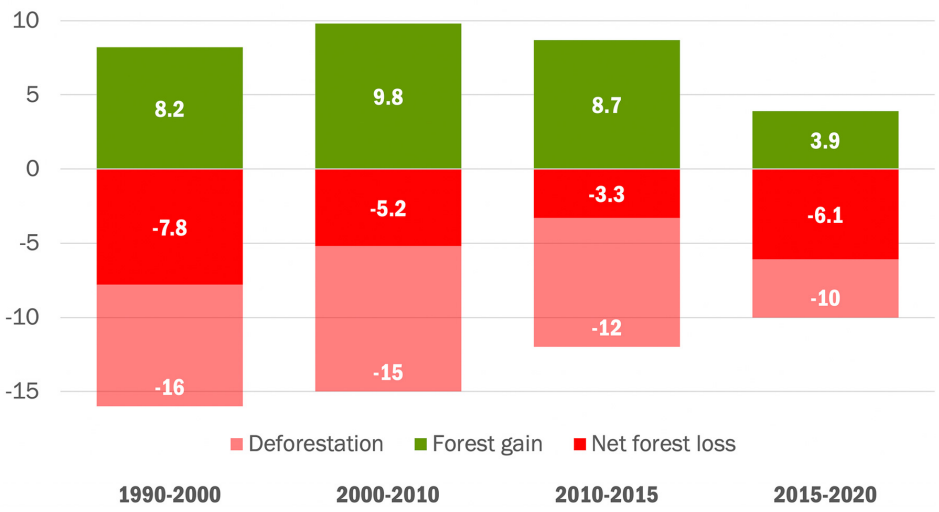


Figure 1: Net Annual Forest Loss. For each period the figure shows estimates of annual global deforestation, annual global gains in forest areas, and the net loss, all in millions of hectares. During 2015–2020 annual deforestation was about 10 million hectares, but this was partially offset by 3.9 million hectares of forest gain, for a net annual loss of 6.1 million hectares. Source: United Nations' Food and Agriculture Organization (2020*b*) and https://rainforests.mongabay.com/deforestation/.

about 10 million hectares per year of deforestation, which was partly offset by about 4 million hectares per year of forest gain, for an annual net forest loss of about 6 million hectares. The rate of net forest loss has been changing over time; as Figure 1 shows, it was greatest during the 1990s, declined through 2015, but increased again during 2015–2020, largely because of a reduction in forest gain.

Deforestation occurs because land is valuable, and can be used for agriculture, cattle grazing, mining, and other economic activities.[4] And that is one of the main reasons why we are not planting trees in sufficient number to have a significant impact on net CO_2 emissions. Planting and maintaining trees requires valuable land, which can make it costly. The nature and extent of these and other costs will be explored in this paper.

Suppose deforestation at recent rates continues. What impact would an ongoing loss of, say, 6 million hectares per year have for net CO_2 emissions? Each year CO_2 absorption would be reduced by $6 \times 10^6 \times 500 \times .02 = .06$ Gt per year, or about 1 Gt after 17 years. But net emissions would actually increase by much more, because a tree contains about 200 kg of carbon, which releases around $200 \times 3.67 \approx 700$ kg of CO_2 when the fallen tree decays

[4]For a detailed discussion of deforestation in different parts of the world, and recent research to better understand the causes and effects of deforestation, see Balboni et al. (2023).

or (more often) is burned. This implies that an ongoing loss of 6 million hectares per year would increase net CO_2 emissions by 0.27 Gt per year, or about 1 Gt after four years.[5]

Deforestation can be offset to some extent by *forestation*, which is our focus. How many hectares can be forested, and at what cost? There are estimates based on satellite data, such as the 1-billion hectare estimate from Bastin et al. (2019) used above. These macro-level estimates attempt to account for land that is potentially forestable, but tell us little about forestation costs. Those costs vary considerably across regions due to regional differences in land use, and in rainfall and other climatic factors that affect forest growth.

We address this problem at the micro level and develop a supply curve for forest-based CO_2 removal. Given data limitations, we focus on forested and forestable areas in South America, which include the Amazon rainforest (accounting for 13 percent of the world's total forest area), the Atlantic forest, the Gran Chaco region, and areas of savanna and grassland. Although our study is limited to South America, with sufficient data our methodology can be applied to other regions, so that a complete global supply curve could be constructed.

We consider planting trees in areas that during the past 50 years were forested but experienced forest loss, as well as areas that were never forested and instead existed as savanna or grassland. However, some recent studies have suggested that the forestation of areas that never existed as forest can have negative environmental repercussions, and thus some argue should be avoided.[6] Flora and fauna that can survive in a savanna, for example, might not survive in a dense forest, so turning savanna into forest could reduce biodiversity. We do not take a stand on this issue, but for comparison, we also develop a supply curve that restricts potentially forestable land to those areas that were previously forested.

We account for the three most important types of cost involved in forestation:

1. **Opportunity cost of land.** This varies greatly across locations, and is often the largest cost component for forestation. Deforestation occurs because land has economic value, and foresting a hectare of land means it cannot be used for other purposes.

[5] 1 kg of carbon is equivalent to 3.67 kg of CO_2 because of the two oxygen atoms. Tropical moist forests contain about 130 tons of carbon per hectare above ground (Figure 6 in ForestPlots.net et al. (2021)) and 34 tons below ground (Mokany, Raison and Prokushkin, 2006). Tree density is in the range of 550-650 trees/ha (ForestPlots.net et al., 2021; Crowther et al., 2015), implying an average of 270 kg of carbon per tree. For temperate deciduous and coniferous forests the carbon content is lower, so 200 kg is a conservative average number. See Ramankutty et al. (2007). That CO_2 enters the atmosphere fairly quickly, but to measure its impact on temperature, we can "amortize" it over 10 years, so it is roughly equivalent to additional CO_2 emissions of $700/10 = 70$ kg of CO_2 per year. See Amazon Fund (2010) and Franklin and Pindyck (2018). Adding that to the 20 kg of lost absorption yields 90 kg of CO_2 per year for each tree cut down, and with 500 trees per hectare this implies an increase in net emissions of $6 \times 10^6 \times 500 \times .09 = .27$ Gt per year.

[6] See, e.g., Pörtner et al. (2021) and Holl and Brancalion (2020).

2. **Planting and maintenance costs.** Forestation begins with planting and growing seedlings, and then replanting those seedlings with fertilizer, water, and insecticides. Later, the trees must be protected from severe weather and pruned as they mature, and sometimes replanted. Mature trees have ongoing maintenance costs, which includes continual addition of fertilizer and insecticides, and depending on the area, water.

3. **Forest conservation costs.** Later, mature trees must be protected from illegal logging, which is a serious problem in much of the world. Monitoring and law enforcement efforts must be put in place in order to ensure forest conservation.

Given these costs, we determine where and how many trees can feasibly be planted. We mentioned water as a critical input; indeed forestation in areas with limited rainfall is usually prohibitively expensive, and most areas suitable for forestation have considerable rainfall. We therefore consider areas where precipitation patterns can potentially support forest growth.

As explained in more detail below, we begin by examining tree cover distributions and precipitation patterns in tropical and subtropical regions *worldwide*, using a $0.5^\circ \times 0.5^\circ$ resolution land grid. The objective is to determine where precipitation patterns make it economical to plant trees and the number of trees that should be planted on each land grid element. Turning to South America, we then estimate the land opportunity, tree planting and forest conservation costs for each $0.5^\circ \times 0.5^\circ$ resolution land grid element. Combining this with estimates of the CO_2 absorption rate per hectare and per tree, we compute the marginal cost of a one-ton reduction in net CO_2 emissions via forestation. Then, starting with the lowest-cost opportunities for CO_2 removal, we build up the supply curve.

Of course forestation can have different objectives, and much of it is done to produce timber and other wood products. Timber producers plant trees, cut them down at or before maturity, plant new ones, and so on, with the total number of trees roughly constant over time. Hence we ignore timber production and focus on forestation with the objective of removing atmospheric CO_2.

Trees eventually die and when they do, most of the carbon they have sequestered will be released into the atmosphere as CO_2. However, trees can live for up to a few hundred years, and if they are in an area that is fully or nearly fully forested, after they die regeneration will occur naturally. Thus, trees planted now will sequester CO_2 over the 50-year time horizon on which our supply curve is based, and with regrowth for many years afterwards.

In the next section we briefly review the prior literature on the use of forestation to absorb CO_2, and how our approach differs. Section 2 provides an overview of the sources and coverage of our data. In Section 3 we show how the data are used to identify areas with

high precipitation and potential for increased tree cover. Section 4 presents our estimates of land opportunity, tree planting and forest conservation costs in different locations. In Section 5 we use these results to build a supply curve for forest-based CO_2 removal, and we examine the sensitivity of the supply curve to certain assumptions in Section 6. Section 7 concludes with some caveats, policy implications, and suggestions for further work.

1 Related Studies versus Our Approach

Others have addressed the potential of forestation for atmospheric CO_2 removal, but typically using a "top-down" approach with models that simulate the aggregate response of abatement suppliers to a variable carbon price. This contrasts with our "bottom-up" approach, which accounts for local cost data. Some studies used a revealed-preference approach to estimate country-specific relationships between land-use choices and relative returns in the forest and agricultural sectors (Stavins (1999) and Lubowski, Plantinga and Stavins (2006)). Others used regression models or optimal control models to forecast global forest mitigation potential and costs (Busch et al. (2019), Austin et al. (2020)). Here we briefly summarize some recent top-down studies, and explain the need for a bottom-up approach like ours.

Favero, Mendelsohn and Sohngen (2017) combined two large models, a "global dynamic forest model" and a "global mitigation model" (an integrated assessment model) to study whether to use forestland for biomass burning or for carbon storage given alternative carbon price paths. Their model describes the dynamics of woody biomass and forest carbon sequestration demand and supply over time, and for each price path determines the optimal amount of forest, the mix of managed versus natural forest, and how planting and rotation length should be adjusted on managed land. Their results generally support the potential of forestation for reducing net CO_2 emissions.

Busch et al. (2019) used a regression model to estimate how forestation responds to changes in agricultural prices, using data on spatially disaggregated forest cover gain over the two years 2000 and 2010. Their dependent variable is the fraction of a cell area that undergoes a non-forest to forest transition, and the main independent variable is the 30-year present value of the maximum potential revenue stream were the land used for agriculture, which they treat as the land use opportunity cost. Assuming forestation occurs if the carbon price exceeds this opportunity cost, they replace the potential agricultural revenue by a carbon price incentive variable, and trace out marginal cost curves for forestation by projecting areas that would undergo forestation at varying carbon prices. They then simulate forestation (and

resulting CO_2 removal) during 2020 to 2050 from alternative carbon prices.[7]

Austin et al. (2020) estimated forestation costs using an optimal control model of the global timber market to simulate how forests and forest management change over time because of both ecological and market forces. Higher timber prices incentivize more mitigation via rotation and other forest management activities. The authors considered forest regeneration costs and land rental costs, but their focus was on forest management, so theirs is a global model that is not specific to any biome or geography.

Two recent studies also support the view that forest conservation and restoration can contribute to carbon sequestration. Mo et al. (2023) and Walker et al. (2022), respectively, estimate that the total global carbon stock for living tree biomass (above and below ground) is currently 217 and 224 Gt of carbon below its full potential, of which 123 and 152 Gt is in tropical regions. Their estimates are based on the carbon stock that would exist under current climate conditions in the "hypothetical absence of human influence." The global carbon stock for living tree biomass accounts for overall carbon gains (e.g., forest growth) and losses (e.g., forest fires) over time. Averaging these two studies, tropical forests worldwide can store an additional 138 Gt C. If that 138 Gt C materializes over 50 years, global annual CO_2 removal from natural forest growth could reach $(138 \times 3.67)/50 = 10$ Gt CO_2.

In another study, Busch et al. (2024) used regression models to estimate land opportunity and tree planting costs worldwide, and then developed a GHG abatement cost curve for natural regeneration and new planting. They used spatially disaggregated data on carbon and costs (as we do here), but their land opportunity cost estimates are based on actual revenue and household survey data, while ours are based on potential revenue and average rental values. They find that for 138 low- and middle-income countries, about 2 billion tons of CO_2 per year can be abated via reforestation at a cost below \$50 per ton of CO_2.[8]

These studies provide information on forestation potential and its relation to agricultural revenues and price incentives. But they lack the granular detail needed to show where forestation is best targeted, and its cost. Land opportunity and tree planting costs vary considerably across regions, as does precipitation. Thus much can be gained by a (micro level) bottom-up approach to the use of forestation for CO_2 removal. To show why, Figure 2 presents one of our main results — a supply curve for forest-based atmospheric CO_2 removal

[7]Their land opportunity cost reflects agricultural revenues but ignores costs. Other variables in their model are site characteristics such as slope, elevation, distance from cities, and initial forest cover.

[8]We believe potential revenue better reflects land users' opportunity costs over the long run (e.g., 50 years), while actual revenue may be adequate for the short run. Other differences between their study and ours include options for alternative land use and forest recovery techniques, the approach for identifying the forestation target zone, and whether agroforestry systems and forest conservation costs are accounted for.

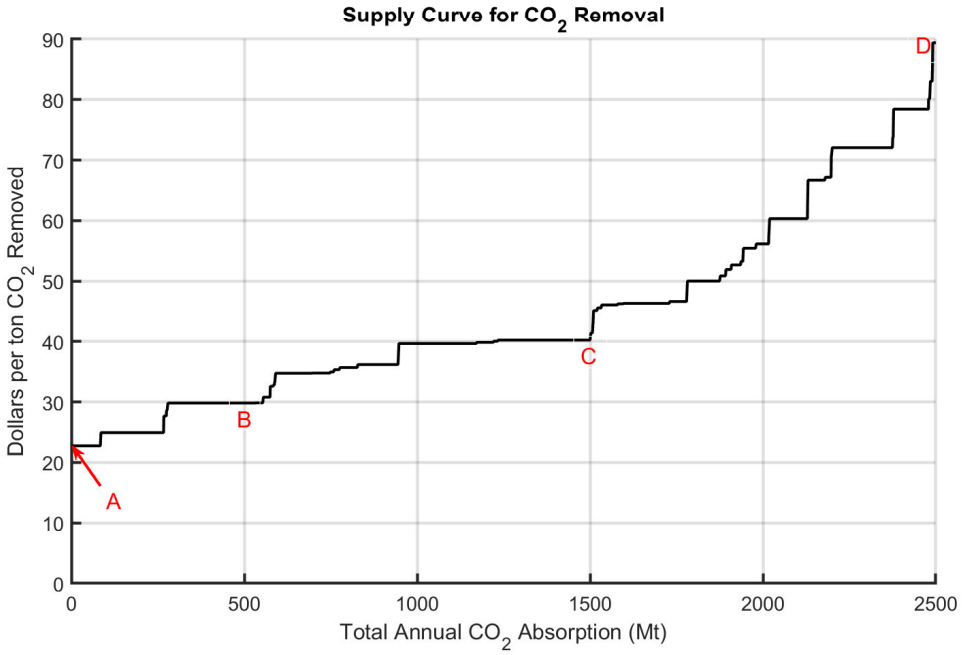


Figure 2: Supply Curve for Forest-Based Atmospheric CO_2 Removal in South America. The curve shows the marginal cost (in 2020 US dollars) of removing one ton of CO_2 as a function of total forest-based CO_2 removal. Each point on the curve corresponds to a $0.5° \times 0.5°$ resolution land grid element.

in South America. The curve shows the marginal cost of removing (via forestation) one ton of CO_2 as a function of total forest-based annual CO_2 removal. Each point on the curve corresponds to a $0.5° \times 0.5°$ resolution land grid element.

Point A on the curve shows the lowest cost ($23 per ton) at which CO_2 can be removed from the atmosphere by planting and maintaining trees in South America. It applies to a land grid element in the Amazon forest of Brazil, state of Pará, at location (-57.75° longitude, 1.25° latitude). This is the lowest-cost location in part because of plentiful rainfall, but also because of relatively low tree planting and land opportunity costs.[9]

Point B is also in the Amazon forest of Brazil, state of Pará, at location (-49.25°, -4.25°). Here, too, rainfall is plentiful, but tree planting costs are higher, so the cost of removing CO_2 is $30 per ton. Point C is in the Amazon forest of Brazil, state of Mato Grosso, at location (-53.75°, -14.75°). Land opportunity costs are higher so the cost of removing CO_2 is $40 per ton. Finally, Point D, at the top of the curve, is in the Brazilian Cerrado at location (-49.75°, -20.25°). This area is largely savanna, with lower forestation potential and higher

[9]There are 160 land grid elements with the same $23 per ton marginal cost spread across 8 Amazon countries. They are all on the short horizontal line that begins at Point A.

land opportunity costs, so the cost of removing CO_2 is about \$90 per ton. (Details regarding points A, B, C and D are in the Appendix in Table A1.)

Figure 2 shows that regional variations in marginal cost are large. The cost breakdown also varies regionally. Table A1 shows that the land opportunity cost accounts for about half of full marginal cost at Point A on the supply curve, but about 75% at Point D. To account for these variations in rainfall, forestation costs, tree densities, and CO_2 absorption rates, we work at the spatially disaggregated level of $0.5^\circ \times 0.5^\circ$ resolution land grid elements.

2 Data

To build the supply curve we must determine where in South America it is economical to plant trees, how many trees can be planted, and the full cost of planting and maintaining those trees. Table A2 shows summary statistics for some of the key variables, and Table A3 summarizes the input data and corresponding web-based data sources.

2.1 Climate, vegetation, and borders

Given the importance of water, we first examine tree cover distributions and rainfall patterns in tropical and subtropical regions around the world. The objective is to determine the relationship between tree cover and precipitation. Precipitation is described by a combined measure of average rainfall volume and average dry season intensity (the difference between precipitation and evapotranspiration). From the observed relationship, we determine the areas where precipitation patterns can support forest growth.

Annual tree cover data were extracted from the publicly available website of Moderate Resolution Imaging Spectroradiometer/Vegetation Continuous Fields (MODIS/VCF), and monthly precipitation data were extracted from the publicly available website of Climatic Research Unit Gridded Time Series (CRU/TS).[10] Monthly precipitation data are available at 0.5° resolution (approximately 50 km latitude and longitude, i.e., 2,500 km^2 = 250,000 ha), while the annual tree cover data from MODIS/VCF are available at a 250-meter resolution

[10]MODIS is a satellite-based sensor used for earth and climate measurements, and MODIS/VCF contains annual tree cover data (with years beginning on day 65, i.e., from March through February). MODIS/VCF provides a global representation of surface vegetation cover at a 250-meter spatial resolution, and has three ground cover components: percent tree cover, percent non-tree cover, and percent non-vegetated (DiMiceli et al. (2020)). The CRU/TS product is a widely used climate dataset with a 0.5° latitude by 0.5° longitude grid over all land domains of the world except Antarctica, derived by the interpolation of monthly climate anomalies from extensive networks of weather station observations (Harris et al. (2020)).

(0.0625 km^2 = 6.25 ha).[11] To ensure that the tree cover and precipitation data apply to the same time periods and land grid elements, annual values of rainfall volume and dry season intensity were computed from March through February, and tree cover values were sampled at the centroid of each corresponding precipitation land grid element.

Using the tree cover data from MODIS/VCF, we also derive the relationships between percent tree cover, tree density (stems per hectare), and CO_2 absorption rates in the tropics. Estimates of tree densities were obtained from ForestPlots.net et al. (2021) and Crowther et al. (2015). Estimates of carbon gains and CO_2 absorption rates were obtained from ForestPlots.net et al. (2021), Sullivan et al. (2020*b*), and Mokany, Raison and Prokushkin (2006). In particular, Figure 6 in ForestPlots.net et al. (2021) and Figure 1 in Crowther et al. (2015) show that the average tree density in tropical moist forests worldwide is about 600 trees per hectare. These estimates were used to determine the average CO_2 absorption rate per tree in South America's tropical and subtropical regions (Section 3.3).

To work at the level of land grid elements, we must delineate the borders of different biomes, and the borders of the countries (or states) where these biomes are located. The Amazon forest includes territory belonging to nine nations, with about 60% in Brazil, 13% in Peru, 10% in Colombia, and smaller amounts in six other countries. The Atlantic forest includes territory belonging to three nations, with 92% in Brazil, 6% in Paraguay, and 2% in Argentina. The Gran Chaco region is in three countries, with about half in Argentina, a third in Paraguay, and the rest in Bolivia. We obtained the borders of the Amazon rainforest from the Brazilian Institute for Space Research (INPE), the borders of the Atlantic forest and Gran Chaco region from the MapBiomas Project (http://mapbiomas.org), the borders of South American countries from the Global Administrative Database (GADM), and the borders of Brazilian states from the Brazilian Institute of Geography and Statistics (IBGE).

2.2 Economic data

Land opportunity cost is particularly important. Most land that is not forested (or was deforested) is used to produce food products in three general ways: grow and harvest temporary crops (e.g., soy, corn and other grains, and vegetables); grow and harvest permanent crops (largely tree-growing crops such as apples, avocados, coffee and palm); and raise livestock for meat and milk. Farmers incur operating and overhead expenses, so land opportunity costs should not be confused with gross production values. If land is currently being used for

[11] One degree latitude or longitude near the equator is equivalent to 111 km, so one degree in the tropics is approximately 100 km, and 0.5° resolution is 50 km.

agricultural purposes, its opportunity cost is just gross revenue minus total operating costs, where the latter excludes rents or other costs associated with the use of the land.

Land opportunity costs in Brazil for the most important temporary crops (soy and corn), permanent crops (coffee and oranges) and livestock (bovine meat and milk) were obtained by request from the Brazilian Confederation of Agriculture and Livestock (CNA).[12] The CNA collects data on agricultural production costs by conducting meetings with farmers, input providers, and technical experts in Brazilian states and cities. From these meetings, the CNA derives information about agricultural production costs, including the opportunity cost of land, for agricultural activities in different regions. The land opportunity costs that we use here were derived by the CNA through the consensus reached among meeting participants (most often based on rental contracts through which farmers rented land) during 2018-2020.

Brazil has 26 states and one federal district, which are grouped into five regions. We do not have data on land opportunity costs in all Brazilian states, but only for several states in each region. Using that data, we estimated the land opportunity costs for each Brazilian state as the average rental value for each agricultural activity in the corresponding region. For South American countries other than Brazil, we use the average land opportunity costs in the Brazilian regions closest to their frontiers. Table A4 shows land opportunity costs for each agricultural activity in each Brazilian region and in other South American countries in 2018-2020. We use these numbers to derive land opportunity costs for each land grid element, as explained in Section 4.1.

Land opportunity costs have grown steadily over the past few decades, and we assume they will continue to grow over the next 50 years at a rate equal to the Brazilian gross agricultural production value growth rate over 2010 to 2020. Gross production values for temporary and permanent crops in each Brazilian state were obtained from the Brazilian Institute of Geography and Statistics (IBGE), and gross production values of livestock (bovine meat and milk) in each state were obtained from the Brazilian Ministry of Agriculture and Livestock (MAPA). The average growth rate for both was 4% per year.

Tree planting and maintenance costs depend on the choice of forest recovery technique, which in turn depends on such factors as soil degradation, work scale, possibility of mechanization, and, most importantly, tree cover. Kishinami and Watanabe Jr. (2016) and Benini and Adeodato (2017) provide estimates of tree planting and maintenance costs for the most widely used forest recovery techniques. As explained in Section 4.2, we use these estimates to determine planting and maintenance costs for each land grid element.

[12] These products are respectively responsible for 62%, 50% and 60% of the gross production values of all temporary crops, permanent crops and livestock in Brazil.

Forest conservation costs depend on governments' conservation policies and budgets. Cunha et al. (2016) and Assunção, Gandour and Rocha (2023) provide estimates for the forest conservation costs incurred by Brazil from 2000 to 2014. As explained in Section 4.3, we use these estimates to derive the forest conservation cost numbers used in our model.

The land areas used for growing temporary and permanent crops in each Brazilian state were obtained from the Brazilian Institute of Geography and Statistics (IBGE), and the land areas used for raising livestock were obtained from the MapBiomas Project (see http://mapbiomas.org). The land areas used for growing temporary and permanent crops and raising livestock in each South American country were obtained from the United Nations' Food and Agriculture Organization. (In Section 5, we discuss the planted and pasture areas in different Brazilian states and South American countries.)

3 Forestation Targets

Tree growth requires water, which in many parts of the world is expensive, making forestation uneconomical. Thus, we need to determine the areas where precipitation patterns make it economical to plant new trees, and the number of trees that could be planted in each area.

3.1 Where to plant trees

We look for areas where precipitation patterns support forest growth. We start by investigating the relationship between tree cover and precipitation patterns in tropical and subtropical regions around the world, in order to draw insights that help define the economically efficient forestation target zone in South America.

Several studies have examined the relationship between tree cover and precipitation patterns, with the latter described by a measure of rainfall volume (the mean annual precipitation, MAP) and dry season intensity (the mean maximum cumulative water deficit MMCWD).[13] Hirota et al. (2011) found that tree cover does not increase steadily with rainfall (MAP), but instead is constrained to ranges that could be identified as treeless (0 to 5% tree cover), savanna (around 20%) or tropical forest (around 80%). It is rare for tree cover to remain between 40 and 60% over a sustained period, consistent with the view that feed-

[13]The maximum cumulative water deficit (MCWD) is the maximum value of the monthly accumulated water deficit (i.e., difference between precipitation and evapotranspiration) reached on a given piece of land in a given year. The details of the MCWD calculation is described in Aragão et al. (2007). The annual precipitation (AP) and maximum cumulative water deficit (MCWD) are calculated for several years and averaged to yield the means (MAP and MMCWD).

back loops (including fire spread feedbacks) move the ecosystem closer to either the forest or savanna state.[14] Suppl. Figure 1 in Zemp et al. (2017) illustrates how tropical forests can be found in areas where MAP $>$ 1,000 mm/yr *or* dry season intensity MMCWD $<$ 400 mm/yr. Our results are consistent with these earlier studies.

We use tree cover data from MODIS/VCF to estimate the probability distributions of tree cover in tropical and subtropical regions of South America (SAM), Africa (AFR) and Asia and Oceania (AOC). We then use precipitation data from CRU/TS to investigate the relationships between tree cover and rainfall volume, and between tree cover and dry season intensity, both worldwide. For each land grid element within latitudes $[-35, +15]$, we collected time series of yearly tree cover (2001 to 2018) and monthly rainfall (March 2001 to February 2019), and calculated the mean annual precipitation (MAP), mean maximum cumulative water deficit (MMCWD) and average tree cover (ATC) over 2001–2018. There are 8009 land grid elements over these latitudes worldwide, giving us 8009 samples of MAP, MMCWD and ATC. From these samples, we obtained kernel density estimates of tree cover distributions for these three continents, and joint probability distributions of ATC, MAP, and MMCWD worldwide.[15]

Figure 3 shows the probability distributions of average tree cover (ATC) in SAM, AFR, and AOC. The distributions differ across these three continents, but they all have peaks at the characteristic tree cover of forest (around 75%) and savanna (around 20%). This is consistent with models of forest evolution that show how low and high tree cover are stable equilibria.[16] Figures 4a and 4b show kernel density estimates of the joint probability distributions for ATC and MAP, and for ATC and MMCWD, again using worldwide data, but now combining SAM, AFR, and AOC. In these two-dimensional graphs, the magnitude of the probability density is shown by the darkness of the shading. As with Figure 3, these graphs show that the characteristic tree cover of forest and savanna dominate. But the graphs also show that high tree cover can be found in areas where MAP $>$ 1,000 mm/yr *or* MMCWD $<$ 400 (mm/yr). Likewise, low tree cover is found in areas with low annual

[14] Fire spread depends on a continuous grass layer, so the higher the tree cover, the lower the fire spread is (i.e., the more fire-resilient the forest is), and vice-versa (Staver, Archibald and Levin (2011)). Franklin and Pindyck (2018) show how deforestation can tip an ecosystem from the forest to the savanna state.

[15] Silverman (1986) shows that for a Gaussian kernel and most unimodal and bimodal underlying distributions, the optimal window width is $h = 0.9 \times A \times n^{-1/5}$, where $A =$ min (standard deviation, interquartile range/1.34), and n is the sample size. We used two kernel smoothing routines in R, geom_density and stat_density2d, with normal kernel functions and bandwidth suggested by Silverman (1986). Land grids in the treeless state (0-5%) were removed to avoid distortions caused by human activity.

[16] See, e.g., Hirota et al. (2011), Zemp et al. (2017), Staal et al. (2018) and Franklin and Pindyck (2018).

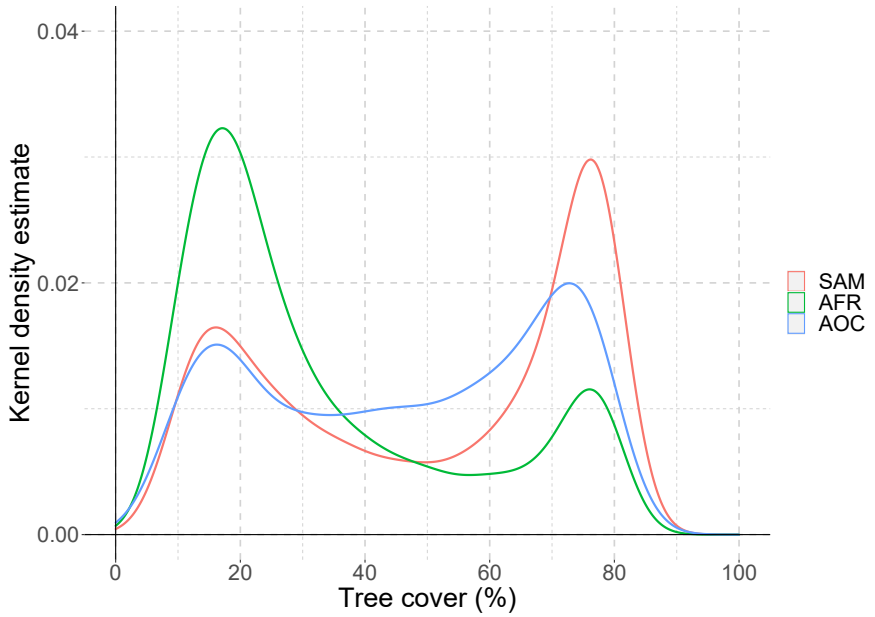


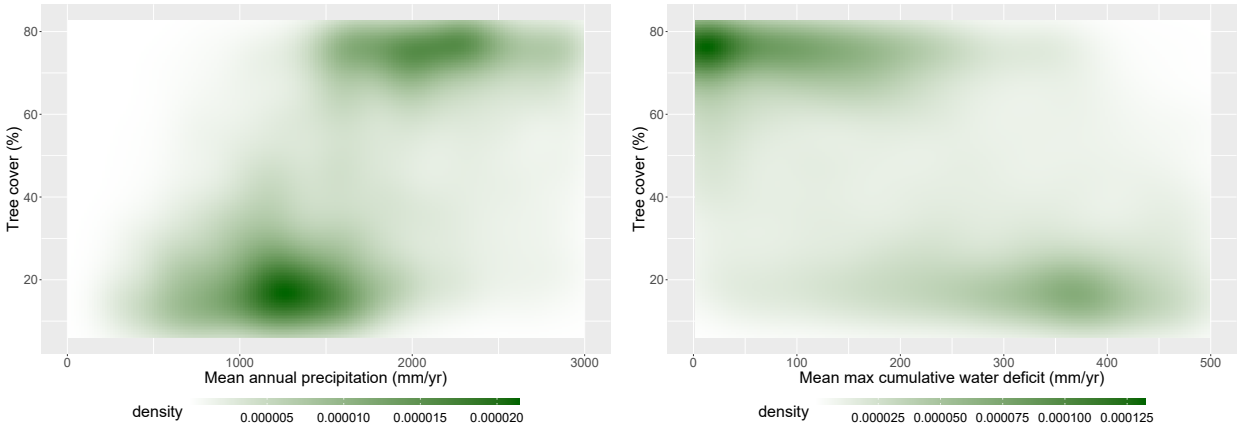
Figure 3: Probability Distributions of the Average Tree Cover from 2001 to 2018 in Tropical and Subtropical Regions of South America (SAM), Africa (AFR), and Asia and Oceania (AOC). Note the peaks at low (10 to 30%) and high (70 to 80%) tree cover, corresponding to savanna and fully forested, respectively.

precipitation and/or high maximum water deficits. Thus, these precipitation conditions are necessary for the development and sustainability of dense tropical forests.

We therefore take the forestation target zone in South America to be those areas with mean annual precipitation at or above 1,000 mm/yr and mean maximum cumulative water deficit at or below 400 mm/yr. The forestation target zone is shown in Figure 5.

3.2 Target tree cover and forestation potential

We now estimate the forestation potential for each land grid candidate for forestation in the target zone. We base the forestation potential on the characteristic tree cover of the biome that previously existed in the land grid element. Thus, for land grids that during the past 50 years were once densely forested but have experienced forest loss, including areas of the Amazon rainforest, Atlantic forest and Gran Chaco region, we use the tree cover target of 75%, which is the characteristic tree cover of forest, and we assume this target can be reached and maintained over the long run. In areas that were never densely forested, going from a low tree cover (e.g., 20%) to 75% may not be feasible over the long run. Figures 3 and 4 show that the tree cover rarely remains between 40 and 60% over a sustained period. Thus, for land grids that are in the target zone but existed as savanna (e.g., Cerrado) or grassland



(a) Tree cover and annual precipitation.

(b) Tree cover and max. cumulative water deficit.

Figure 4: Bivariate Probability Distributions for 18-Year Averages of Tree Cover, Annual Precipitation and Maximum Cumulative Water Deficit (2001-2018). The magnitude of the probability density is shown by the darkness of the shading.

(e.g., Pampas), we use a tree cover target of 40%. This is higher than the characteristic tree cover of savanna, but below the unstable range of 40-60%.

The forestation potential for each land grid candidate is the difference between the target tree cover (either 75% or 40%) and current tree cover. Figure 6 shows the average tree cover observed from remote sensing (MODIS/ VCF) in 2016-2018, and the forestation potential calculated for each land grid candidate. We treat areas with 75% tree cover as "fully forested."

3.3 Tree density, CO_2 absorption rate, and forestable area

A single tree can absorb 10 to 40 kg of CO_2 per year, depending on climate and the age and type of tree, so to estimate the average CO_2 absorption rate for a land grid element, we must account for the trees it contains (or will contain following forestation). Organic carbon accumulates in both above and below ground biomass (AGB and BGB). Patterns of above ground biomass (stems, bark, branches) are well understood, but we know less about below ground biomass (roots) because it is difficult to observe and measure root biomass. The below ground biomass is usually expressed as a fraction of the above ground biomass using an estimated "root-to-shoot" ratio, which is the amount of plant tissue with supportive functions (root biomass) divided by the amount with growth function (shoot biomass).[17]

To estimate the CO_2 absorption rate per tree, we start with the above ground biomass (AGB). As trees age, the rate at which they absorb carbon falls; a 5 to 10 year old tree

[17]Mokany, Raison and Prokushkin (2006) review root-shoot ratio estimates for major terrestrial biomes.

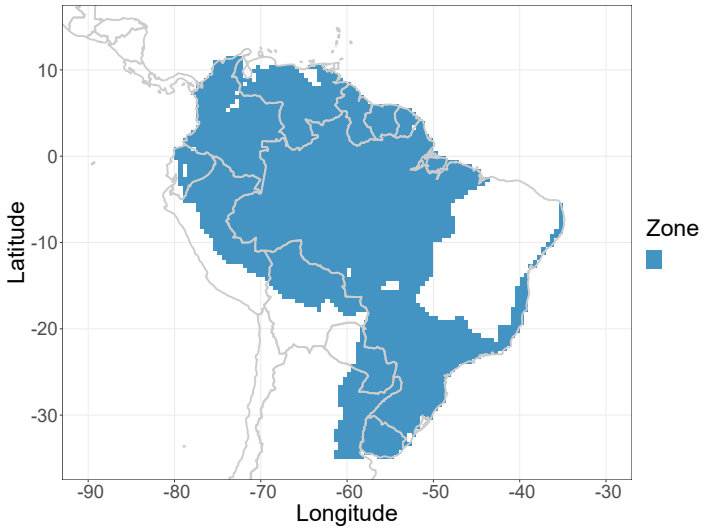


Figure 5: Forestation Target Zone. The areas where precipitation patterns support forest growth (i.e., MAP $\geq$ 1,000 and MMCWD $\leq$ 400 mm/yr) are in blue.

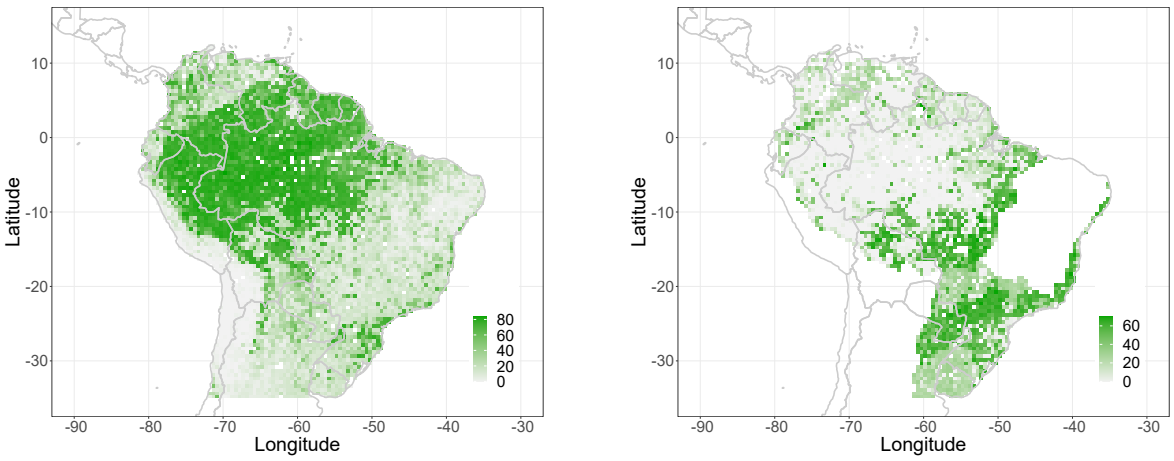
will absorb twice as much carbon as the same tree when it is 50 years old. Forestation today involves planting new trees which, with maintenance and possible replanting, will last at least 50 years, so we want the average carbon absorption rate over 50 years. For trees in tropical moist forests, several studies put the average carbon stock accumulation above ground at about 2.4 tons of carbon per hectare per year.[18] The AGB absorption can vary, depending on tree density and location; using the data package provided by Sullivan et al. (2020*b*) (available at Sullivan et al. (2020*a*)), we derived the distribution for the above ground carbon accumulation, and calculated a mean and standard deviation of 2.4 and 0.6 respectively. These numbers are consistent with estimates by others of carbon stock accumulation, as shown in Table A6 in the Appendix.

For the below ground biomass (BGB), we use a root-shoot ratio of 0.26.[19] Multiplying the AGB by 1.26, the total carbon stock accumulation (above and below ground) is 3.0 tons of carbon per hectare per year, or $3.0 \times 3.67 = 11$ tons of CO_2. Given an average tree density of 600 trees per hectare, the average CO_2 absorption rate is $11,000/600 = 18.33$ kg CO_2 per tree per year. These estimates apply to trees in tropical moist forests; we use them because precipitation patterns in the target zone are similar to those in tropical forests.

This value of 18.33 kg probably underestimates the true rate of CO_2 absorption, because

[18]See Fig. 6 in ForestPlots.net et al. (2021), Fig. 1 in Sullivan et al. (2020*b*), and Sullivan et al. (2020*a*).

[19]Here we follow Harris et al. (2012) and Busch and Engelmann (2015). This estimate is based on a regression model of root biomass (y) as a function of shoot biomass (x), using data from forests and woodlands, which resulted in $y = 0.26\,x$, with $R^2 = 0.78$. See Figure 3 in Mokany, Raison and Prokushkin (2006).



(a) Current tree cover (%).

(b) Forestation potential (%).

Figure 6: Current Tree Cover (2016-2018) and Forestation Potential over the Forestation Target Zone. Each pixel represents a 0.5° resolution land grid element.

the data from Sullivan et al. (2020*b*) we used to calculate the mean AGB absorption rate applies to a mix of trees of different ages, but with an average age close to 50 years.[20] For example, Smith et al. (2016) obtained a higher number for the net atmospheric removal of carbon for 40 year old trees, namely 3.4 tons of carbon per hectare per year, or, with 600 trees per hectare, $(3.4 \times 3.67)/600 \approx 21$ kg CO_2 per tree per year. We use the 18.33 kg estimate to be conservative, and because it is based on extensive and publicly available data.

For the characteristic tree cover of forest (75%) and 600 trees per hectare, a one percentage point increase in tree cover means going from, say, 40% to 41% tree cover, with an upper limit of 75%. A fully forested hectare has 600 trees, so a 1 percentage point increase means planting $600/75 = 8$ new trees. We assume that these 8 trees are planted so as to allow the effective combination of agriculture and trees, while occupying an area of $8/600 = 1/75 = 0.01333$ hectare.[21] This is the agricultural area that will be lost for forest growth. Then, for a land grid with 250,000 hectares, a 1 percentage point increase in tree cover means planting $8 \times 250,000 = 2$ million trees over an area of $0.01333 \times 250,000 = 3{,}333$ hectares, and will increase the CO_2 absorption rate by $2,000,000 \times 18.333 = 36{,}667$ tons of CO_2 per year.

[20]Fig. 1 in Sullivan et al. (2020*b*) shows that the average carbon residence time in their sample of 273 forest plots is slightly above 50 years. The carbon residence time, calculated as the ratio of living carbon stocks to carbon gains, is a rough measure of tree age.

[21]This assumes an agroforestry system where trees are grown around or among crops or pastureland. The target density of 600 trees per hectare implies a tree spacing of $(0.01)^{0.5}/(600^{0.5}) = 4.082$ meters, so each tree occupies $4.082^2 = 16.663$ m^2, and 8 trees occupy $8 \times 16.663 = 133.3$ m^2 $= 0.01333$ hectare. For more information on agroforestry systems, see https://www.fao.org/forestry/agroforestry/80338/en/.

The potentially forestable area in a geographic unit is the sum of the forestable areas in all land grids inside the unit's borders. Take, for example, two land grids, X and Y, where X has 55% tree cover so its forestation potential is $75\% - 55\% = 20\%$, and Y has 30% tree cover so its forestation potential is 45%. The forestation potential of these two land grids combined is $20+45 = 65$ percentage points. Multiplying that sum by the increase in forested area from a 1 percentage point increase in tree cover (3,333 hectares) yields a potentially forestable area of $65 \times 3,333 = 216{,}645$ hectares. With an average tree density of 600 trees per hectare, $216,645 \times 600 = 130$ million trees can be added to these two land grids.

Summing the forestation potential over all land grids inside the target zone (see Figure 6b) yields 68,400 percentage points. Multiplying by the increase in forested area from a 1 percentage point increase in tree cover (3,333 hectares), we find the potentially forestable area in South America's tropical and subtropical regions is $68,400 \times 3,333 = 228$ million hectares. With 600 trees per hectare, the total number of trees that can be added to the forestation target zone is 228 million $\times$ 600 = 137 billion trees.

The potentially forestable area in each Brazilian state or South American country can be higher or lower than the sum of the areas used for agriculture and livestock. It will be higher, for example, if a large area has been deforested for wood or mining as opposed to agriculture. It will be lower if the area is not completely inside the target zone.

4 Forestation Costs

We estimate the land opportunity, tree planting and forest conservation costs for each land grid element in the target zone. These costs vary over time; land opportunity costs grow as food demand grows, and planting costs are highest during the first few years of forestation, and then fall. However, we treat the CO_2 absorption rate as constant over a 50-year horizon, so to estimate the marginal cost of absorbing CO_2 we smooth out these costs over time.

We calculate the 50-year present value of each flow of cost, and then convert these present values into 50-year annualized costs. We do this using an annual discount rate of 5%, which is approximately the average long term real interest rate on Brazilian government bonds over the last 20 years. For comparison, we also develop a supply curve using a discount rate of 2.5%, based on survey results in Pindyck (2019) and elsewhere.

4.1 Land opportunity costs

Land is used to grow temporary crops, grow permanent crops, or raise livestock, so there are three possible values for the land opportunity cost. We estimate the land opportunity cost

for each agricultural activity in each Brazilian region and in other South American countries.

Of Brazil's five regions, the North has the lowest land opportunity costs for all three agricultural activities, and the South has the highest costs for temporary crops and livestock (2.5 and 3.6 times as large as the North, respectively). Land opportunity cost data are unavailable for other South American countries; given that Brazil accounts for 67% of the entire potentially forestable area of South America, we use the average cost in the Brazilian regions closest to the frontiers of each country. We assume that land opportunity costs will continue to grow over the next 50 years at the 4% real growth rate of the Brazilian gross value of agricultural production from 2010 to 2020.

From the data for 2018-2020 (Table A4), we calculate the 50-year present values for the land opportunity cost for each agricultural activity in the Brazilian regions and South American countries covered by the forestation target zone, and convert these into annualized costs. Table 1 shows these annual land opportunity costs for each agricultural activity.[22]

To illustrate, consider a land grid element with 55% tree cover in northern Brazil, which is used for raising livestock, so its land opportunity cost is \$131 per hectare per year (Table 1). Suppose we increase the tree cover to 75%. A land grid covers 250,000 hectares, so a 1 percentage point increase in tree cover requires $8 \times 250,000 = 2$ million trees, occupying 1.33% of 250,000 = 3,333 hectares that can no longer be used for agriculture. The 20% increase in tree cover requires $20 \times 2,000,000 = 40$ million trees over an area of $20 \times 3,333 =$ 66,660 hectares, so the land opportunity cost is $131 \times 66,660 =$ \$8.7 million per year.

4.2 Tree planting and maintenance costs

The costs of planting and maintaining trees depend on the choice of forest recovery technique, which in turn depends on such factors as soil degradation, work scale, possibility of mechanization, and – most importantly – current tree cover. Different forest recovery techniques imply different activities and inputs, and thus different costs. These activities and inputs can also vary for the same recovery technique, depending on soil and access conditions.

Benini and Adeodato (2017) and Kishinami and Watanabe Jr. (2016) provide cost estimates for the three most widely used forest recovery techniques, based on the range of activities and input requirements. The techniques are: (i) "facilitating natural regeneration," which involves controlling land degradation and enabling the spontaneous restoration

[22]The 50-year present value of an annuity of \$1, discounted at 5%, is $(1-(1+5\%)^{-50})/5\% = 18.26$. The 50-year present value of a growing annuity that begins at \$1 but increases at a 4% annual rate, discounted at 5%, is $(1-(1+4\%)^{50} \times (1+5\%)^{-50})/(5\%-4\%) = 38.03$. Thus, Table 1 was derived by multiplying each entry of Table A4 by $38.03/18.26 = 2.08$.

Table 1: Annual land opportunity costs for temporary crops, permanent crops and livestock in the Brazilian regions and South American countries covered by the forestation target zone (in 2020 US dollars).

Geographic unit	**Temporary crops ($/(ha yr))**	**Permanent crops ($/(ha yr))**	**Livestock ($/(ha yr))**
Brazilian region:			
South (S)	596	614	467
Southeast (SE)	246	717	312
Central-West (CW)	246	717	240
Northeast (NE)	362	935	196
North (N)	242	304	131
Argentina	596	614	467
Bolivia	244	510	185
Colombia	242	304	131
Ecuador	242	304	131
French Guiana	242	304	131
Guyana	242	304	131
Paraguay	421	666	353
Peru	242	304	131
Suriname	242	304	131
Uruguay	596	614	467
Venezuela	242	304	131

of native species; (ii) "enhancing tree density and enrichening," where a large number of trees are planted to increase tree density and improve species diversity; and (iii) "total planting," the most expensive technique, which consists of direct planting of seeds and seedlings.

"Facilitating natural regeneration" is most economical for land grids with high tree cover (55-65%), "enhancing tree density and enrichening" is frequently used for land grids with medium tree cover (30-55%), typically on the margins of remnant forest areas and in large clearings, and "total planting" is used for land grids with low tree cover (5-30%). Economies of scale make it uneconomical to plant small numbers of trees, so we only consider areas with forestation potential of at least 10%. Areas with current tree cover below 5% are too difficult or expensive to forest (e.g., urban and industrial areas, or areas of lakes, rivers, and rocky soil), and are ignored. Areas with tree cover greater than 65% are left for (passive) natural regeneration. Because we work at the spatially disaggregated level of land grid elements, we assume forest recovery takes place in contiguous areas of 250,000 hectares.[23]

[23]According to Kishinami and Watanabe Jr. (2016), "facilitating natural regeneration" requires a high density of regenerative trees, and is recommended when tree cover is 50 to 80%, whereas "enhancing tree

Table 2: Tree planting cost present values and 50-year annualized costs for different forest recovery techniques and biomes (2020 US dollars).

Biome and forest recovery technique	**Present values**		**Annualized costs**
	($/ha)*	**($/tree)**	**$/(tree yr)**
Amazon rainforest, Atlantic forest, Gran Chaco region:			
Facilitating natural regeneration	420	3.50	0.192
Enhancing tree density and enrichening	1,100	4.23	0.232
Total planting (seeds and seedlings) up to 75%	2,700	5.87	0.322
Savannas and grasslands:			
Total planting (seeds and seedlings) up to 40%	1,440	8.00	0.438

*Average tree planting costs per hectare in the Amazon and Atlantic forests were obtained from Benini and Adeodato (2017). For areas of savanna and grassland, where the tree cover target is 40%, we take the tree planting cost per hectare as (40/75) of the value for areas of forest, where the target is 75%.

From the present value estimates in Benini and Adeodato (2017), we calculate the average tree planting cost per hectare for each forest recovery technique in the Amazon and Atlantic forests. These costs depend on the number of trees planted, so we estimate the average cost per tree by dividing the per hectare cost by the average number of trees added to each hectare, which in turn is 8 times the difference between the target tree cover (either 75% or 40%) and its midrange tree cover.[24] We convert these present values into 50-year annualized costs. Table 2 shows the tree planting cost present values and 50-year annualized costs for different forest recover techniques and biomes.

Returning to our example of a land grid element in northern Brazil with 55% tree cover, the forest recovery technique is "facilitating natural regeneration," so the annualized tree planting cost is $0.192 per tree per year (Table 2). The 20% increase in tree cover requires 40 million trees, so the tree planting cost is $40,000,000 \times 0.192 = \$7.7$ million per year.

density and enrichening" is recommended for areas with moderate natural regeneration, with tree cover of 30 to 60%. Other factors also affect the choice of forest recovery technique (e.g., soil degradation, possibility of mechanization, etc.). Without field specific data, we use the tree cover intervals of 55-65% for "facilitating natural regeneration," 30-55% for "enhancing tree density and enrichening," and 5-30% for "total planting."

[24]The midrange tree cover for the forest recovery techniques of facilitating natural regeneration, enhancing tree density and enrichening, and total planting are, respectively, $(55\% + 65\%)/2 = 60\%$, $(30\% + 55\%)/2 = 42.5\%$, and $(5\% + 30\%)/2 = 17.5\%$. Recall that each 1 percentage point increase in tree cover requires 8 trees per hectare (and $8 \times 250,000 = 2$ million trees per land grid element). Note that the number of trees actually planted may exceed the number added because some trees die and must be replanted.

4.3 Forest conservation costs

We utilize data from the Brazilian government's budgeted forest conservation policies from 2000 to 2014. Those data show that Brazil's substantial reduction in annual forest loss after 2004 was accompanied by an increase in forest conservation expenditures. From 2005 to 2014, Brazil spent on average $1.1 billion per year on forest conservation at the federal level, while the annual forest loss dropped by about 40% (Cunha et al. (2016)). Taking all forested areas in the Brazilian Amazon and Atlantic forests (340 million hectares), the annual conservation cost over 2005-2014 was about $(1.1 \times 10^9)/(340 \times 10^6) = \$3.20$ per hectare.

To be conservative, we assume that successful forest conservation requires $4.00 per hectare per year. Thus, the conservation of existing forest areas in the Amazon rainforest, Atlantic forest, and Gran Chaco region (about 550 million hectares) will cost $2.2 billion per year. Adding the potentially forestable area of 228 million hectares (Section 3.3), successful forest conservation will require $3.1 billion per year. Returning to our example of a land grid in northern Brazil with 55% tree cover and livestock as the agricultural activity, a 20% increase in tree cover requires 40 million trees occupying $20 \times 3,333 = 66{,}660$ hectares, so the forest conservation cost will be $4 \times 66,660 = \$0.3$ million per year.

To summarize this example, the total annualized forestation cost to reach and maintain a target tree cover of 75% is $8.7 million (land opportunity cost) + $7.7 million (tree planting cost) + $0.3 million (forest conservation cost) = $16.7 million. The resulting increase in annual CO_2 absorption is $20 \times 36,667 = 0.73$ Mt CO_2. Thus, the cost per ton of CO_2 removed is $16.7/0.73 = \$23$, which corresponds to Point A in Figure 2.

5 A Supply Curve for Forest-Based CO_2 Removal

For each land grid in the target zone, we consider increasing its current tree cover up to its target level (75% or 40%). We know the current tree cover, target tree cover, forestation potential and CO_2 absorption rate, tree planting and forest conservation costs, and land opportunity cost for each agricultural activity. But to determine the land opportunity cost for each land grid we need to know which agricultural activity is performed there.

Planted and pasture areas in the forestation target zone are not georeferenced, so we do not know which activity is performed in each land grid element. However, we do know the planted and pasture areas in each Brazilian state and South American country, from which we calculate the percentages currently used for temporary crops, permanent crops and livestock (Table A5). We use these percentages to estimate the potentially forestable area from each agricultural activity, and the land opportunity cost for each land grid element.

(For example, from the last row of Table A5, we estimate that for Venezuela the potentially forestable area from livestock is $6,840,000 \times 87\% = 5{,}950{,}800$ hectares.)

5.1 Land use

For each geographic unit (Brazilian state or South America country), we estimate the area that can be forested from each agricultural activity by multiplying the potentially forestable area by the percentage of area currently used for each activity. For example, from the first row of Table A5, we estimate that for Brazil, state of Paraná (Brazil-PR), the potentially forestable areas from temporary crops, permanent crops and livestock are respectively 8,714 ($= 0.80 \times 10,892$), 109 ($= 0.01 \times 10,892$), and 2,069 ($= 0.19 \times 10,892$) million hectares.[25]

Starting with all land grid elements inside the target zone with current tree cover above 5%, we remove those with forestation potential below 10% to account for economies of scale. (Later, for comparison, we also estimate a supply curve that includes all land grid elements with any forestation potential.) We assume each land grid element is used for the agricultural activity with lowest land opportunity cost (Table 1), and pick the element with the lowest *total* forestation cost per ton of CO_2 removed. We call this the proposed land use conversion. (The land grid element with minimum total forestation cost per ton of CO_2 removed is in the Amazon forest of Brazil, state of Pará (Brazil-PA), with 55% tree cover, where the lowest-cost activity is livestock; this is Point A in Figure 2.)[26]

We calculate the increase in forested area from the proposed land use conversion, and check whether it is less than the available area (in a state or country) for the lowest cost agricultural activity. If it is, we perform the land use conversion and update the potentially forestable area. If it is not, we convert only the area that is available, and shift the geographic unit's agricultural activity to the next lowest cost activity. For example, for Point A in Figure 2, the increase in forested area from the proposed conversion is $(75 - 55) \times 3,333 = 67$ million hectares, the lowest land opportunity cost activity is livestock, and the potentially forestable area from livestock is $0.91 \times 19,569 = 17{,}808$ million hectares (Table A5). Because the potentially forestable area from livestock exceeds the increase in forested area from the proposed land use conversion ($17,808 > 67$), we perform the conversion, and update the

[25] Recall that the potentially forestable area in a geographic unit may be higher or lower than the sum of the areas currently used for temporary crops, permanent crops and livestock (Section 3.3). The potentially forestable area in Brazil-PR is lower than the sum of these areas: $10,892 < 10,741 + 0,121 + 2,626 = 13,488$.

[26] There are 160 land grid elements with the same (minimum) total forestation cost per tCO_2 removed, all in countries with the lowest land opportunity costs (northern region of Brazil, Colombia, Ecuador, French Guiana, Guyana, Peru, Suriname and Venezuela), restored using the cheapest forest recovery technique (facilitating natural regeneration; for land grids with tree cover in the interval 55-65%).

potentially forestable area (to $17,808 - 67 = 17{,}741$ million hectares). Later, as we move along the supply curve, when Brazil-PA's potentially forestable area from livestock has been depleted, we shift its remaining land grid elements to the next lowest cost activity, temporary crops, for which $0.06 \times 19,569 = 1{,}174$ million hectares are available (Table A5).[27]

We then pick the next land grid element with lowest total forestation cost per ton of CO_2 removed, and repeat the above steps until all land grid elements in the target zone have been forested (from their current tree covers up to their target levels), and the remaining forestable area from each agricultural activity in each geographic unit is reduced to zero.

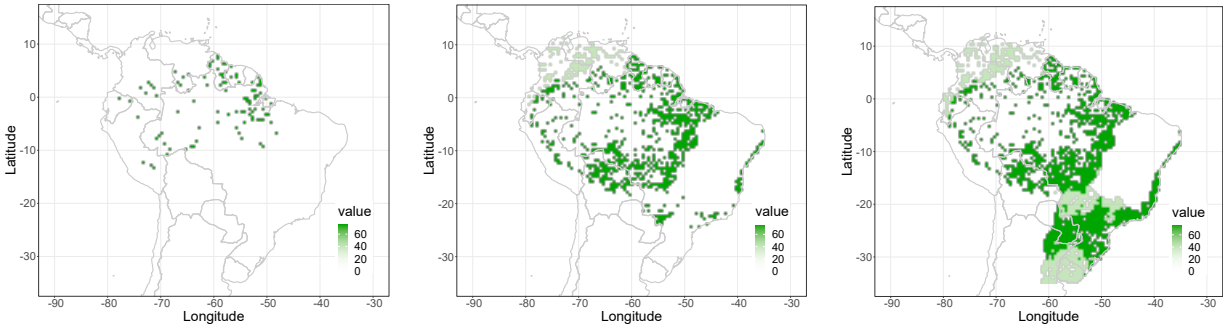
5.2 The supply curve

There are 3,662 land grid elements inside the forestation target zone, of which 3,545 have current tree cover between 5 and 100%. From these 3,545 land grid elements, 1,784 have forestation potential below 10% (either already fully forested or with low forestation potential), leaving 3,545 – 1,784 = 1,761 candidates for forestation. After going through the above steps for the entire target zone, all 1,761 land grid elements were completely forested (either at 75% or 40% tree cover), and the total forested area reached 228 million hectares (equal to the forestable area shown in Section 3.3), with 137 billion new trees planted.

Figure 2 shows the resulting supply curve for forest-based CO_2 removal. Each point on the curve shows the cost per ton of CO_2 removed for a land grid element in the forestation target zone as a function of total annual CO_2 removal. The figure shows that a carbon price at or below \$20/tCO_2 will have no impact on forest-based CO_2 sequestration, a carbon price of \$45/tCO_2 can induce the sequestration of 1.5 Gt of CO_2 per year, and a carbon price of \$90/tCO_2 can induce the sequestration of 2.5 Gt of CO_2 per year.

Figure 7 shows the first 100, 880 and 1,761 land grid elements selected for forestation. Note from Figure 7a that the first 100 land grid elements are in the northern Amazon, across 8 countries, where land opportunity and tree planting costs are lowest. Figure 7b shows that among the first 880 land grid elements most are in the Amazon rainforest, some in the Atlantic and Gran Chaco forests (higher land opportunity costs), and a few in northern South American savannas (higher tree planting costs). Figure 7c shows that most areas of

[27] That happens at point (522 Gt CO_2, \$29.8/t CO_2) on the supply curve (Figure 2), when the 156^{th} land grid element in Brazil-PA is selected for forestation. It has 25% tree cover, so the increase in forested area would be $(75 - 25) \times 3,333 = 167$ million hectares. After the forestation of 155 land grid elements in Brazil-PA, the remaining forestable area from livestock is just 72 million hectares, which is less than the increase in forested area from the proposed conversion, so we perform the conversion only for 72 million hectares, and shift Brazil-PA's remaining land grid elements to the next lowest cost activity, temporary crops.



(a) After 100 land grids. (b) After 880 land grids. (c) After 1,761 land grids.

Figure 7: Land Grids Selected for Forestation and Tree Cover Evolution. Dark green pixels show areas in the Amazon rainforest, Atlantic forest and Gran Chaco region forested at 75% tree cover; light green pixels show savanna and grassland areas forested at 40% tree cover.

savanna and grassland are at the higher end of the supply curve, i.e., these are the most expensive candidates for forestation.

6 Sensitivity of Results

The supply curve in Figure 2 depends on several assumptions: We used a discount rate of 5% to capitalize flows of expenditures; we assumed that all previously forested and unforested land could potentially be forested; and we excluded land grid elements with forestation potential below 10% (on the grounds that scale economies make foresting these locations uneconomical). Here we examine the sensitivity of our results to these assumptions.

Three alternative supply curves are shown in Figure 8, where SC1 is the base case supply curve shown in Figure 2. SC2 is the supply curve that results when the discount rate is lowered from 5% to 2.5%, and is very close to the base case curve. The reason is that lowering the discount rate raises the present value of the flow of expenditures, but lowers the corresponding annualized costs, leaving the annual expenditures nearly unchanged.

To generate SC3, we assumed that only land that had been previously forested during the past 50 years could be reforested now, and excluded land that was never forested but instead existed as savanna or grassland. (Some have argued that foresting areas that never existed as forests could reduce biodiversity and should be avoided.) As expected, SC3 is well above SC1, and the maximum feasible CO_2 absorption is 2 Gt, at a cost of about $85 per ton. It may indeed be the case that foresting land that was previously savanna or grassland could reduce biodiversity (we take no stand on this), but excluding such land is expensive. In any case, Figure 7 shows that areas of savanna and grassland are in the higher end of the

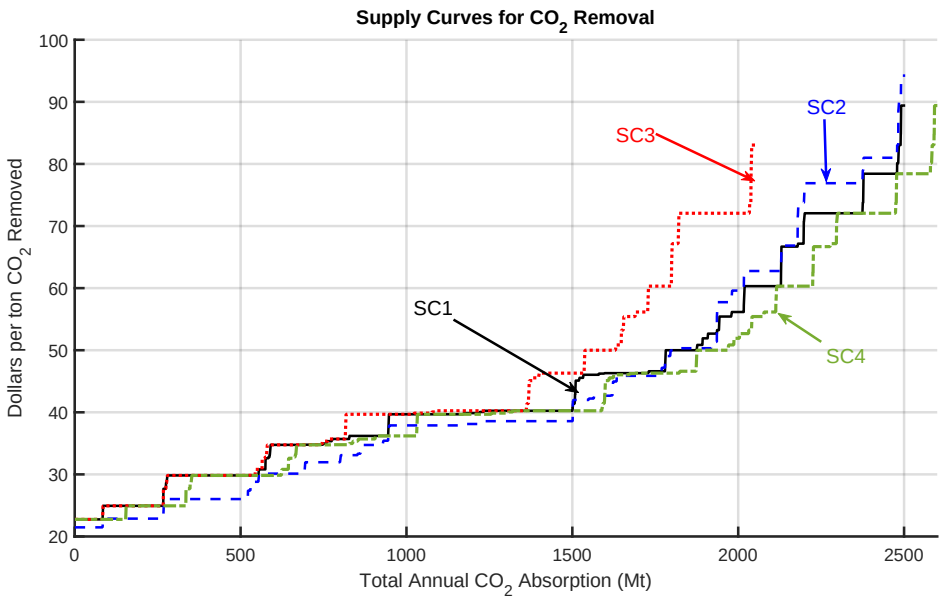


Figure 8: Alternative Supply Curves: SC1 (black) is the base case supply curve described above and shown in Figure 2. SC2 (blue) is the supply curve for a 2.5% discount rate (instead of 5%). SC3 (red) is the supply curve that only includes areas that were previously forested, and SC4 (green) is the curve that results if we include all land grids with any forestation potential (instead of only those with forestation potential above 10%).

base case supply curve (SC1), and these areas are the most expensive to forest.

Finally, SC4 includes *all* land grids with forestation potential, instead of only those with potential above 10%. This change lowers the supply curve, but the difference is small, and only noticeable when total annual CO_2 absorption is above 1.7 Gt.[28] (At a total of 2 Gt the difference in marginal cost is less than $5 per ton.) With the exception of excluding land that was never forested (SC3), our results are not very sensitive to these assumptions.

7 Conclusions

Forestation is seen as a promising way to remove CO_2 from the atmosphere and thereby reduce net CO_2 emissions. But where and how many trees should be planted, and at what cost? Given a price of carbon, how much CO_2 can be removed? We addressed these questions by developing a supply curve for forest-based CO_2 removal in South America. Our supply curve traces out the marginal cost of removing a ton of CO_2 as a function of total annual

[28]The recovery technique "facilitating natural regeneration" is used when tree cover is between 65 and 75%, and "total planting (seeds and seedlings, up to 40%)" is used when tree cover is between 30 and 40%

CO_2 removal. We work at the spatially disaggregated level of $0.5° \times 0.5°$ resolution land grid elements, and each point on the supply curve corresponds to a specific location (grid element), and accounts for land opportunity, tree planting and maintenance costs.

For our base case supply curve, over a billion tons of CO_2 could be removed annually via forestation at a cost below \$45 per ton, and about 2.5 billion tons could be removed at a cost below \$90 per ton. Global annual CO_2 emissions are about 40 Gt, so removing 2.5 Gt would reduce net emissions by about 6 percent. But even at a cost below \$90 per ton (per our base case curve), this reduction is not cheap; a cost of \$90 per ton implies an annual expenditure of \$225 billion. However, if payments are at marginal cost (e.g., \$23 per ton for Point A), the total annual cost of removing 2.5 Gt, found by integrating the area under the supply curve from 0 to 2.5 Gt, would be \$110 billion.

Those costs and CO_2 absorption rates apply to South America. By how much could net CO_2 emissions be reduced worldwide, and at what cost? South America accounts for about 21% of the world's forested area (Food and Agriculture Organization (2020*a*)), and about 23% of the world's forestable area (228 million hectares divided by the 1 billion hectares from Bastin et al. (2019)). If we assume the distributions of tree cover, precipitation, and costs in the rest of the world are similar to those in South America and scale up the supply curve accordingly, we could remove about $4 \times 2.5 = 10$ Gt of CO_2 annually, reducing net emissions by 25 percent.[29] That would cost about $10 \times 90 = \$900$ billion annually if payments were \$90 per ton, or $4 \times 110 = \$440$ billion annually if payments were at marginal cost. The \$900 and \$440 billion values respectively amount to about 0.9 and 0.5 percent of world GDP.

One could take issue with several aspects of our analysis. First, we did not account for the lifetime of trees. When trees die, the carbon they sequestered is released back into the atmosphere as CO_2. Thus, it might seem that planting trees cannot sequester CO_2 over the long run because those trees eventually die. But the key is "eventually." Trees can live for a few hundred years, so trees planted now will sequester CO_2 for many years before they need to be replanted. Also, in a fully forested area with 75% tree cover, trees that die are replaced by natural regrowth (which is why 70 to 80% is an equilibrium tree cover). Our supply curve is based on a 50-year horizon, during which most of the trees planted will survive.

We have ignored potential demand shifts and innovations in agriculture and in forestry that might occur over the coming decades. If consumers' food preferences shift from meat

[29] Applying our results to the rest of the world is a stretch. But Figure 6 in ForestPlots.net et al. (2021) shows probability distributions of tree density and carbon gain in tropical forests in South America, Africa and Asia. Tree densities in these three continents are similar, and carbon gains (and hence CO_2 removal rates) in South America and Africa are similar but a little lower than in Asia.

to grains and vegetables, so that less land is used for livestock and more for temporary and permanent crops, land opportunity costs will change, and may not grow at the assumed rate of 4% per year. Likewise, innovation may lead to reductions in tree planting and maintenance costs. We have no way to predict such changes.

We have also ignored other benefits that forestation can provide, such as water recycling, erosion control, and short-term climate regulation. These benefits have external economic value, and from a public policy perspective should affect the supply curve by reducing the "full" marginal cost of CO_2 removal. Lastly, we have not addressed the cost of maintaining existing forest areas, so as to reduce CO_2 emissions from deforestation, and we have not accounted for the carbon harvested and stored in wood products, nor the net revenue from the sale of wood products.

Trees of different ages and species have different growth rates and therefore store carbon at different rates over time. As explained in Section 3.3, we are taking the average carbon stock, tree density, and CO_2 absorption rate in tropical moist forests in light of the mix of trees already there. We are not considering the impact of forest management on forest growth and carbon stock accumulation. We leave this for further work.

Because data limitations have limited our analysis to South America, this paper might be viewed as a "proof of concept." With sufficient data, however, our method can be extended to forests and forestation in other continents. Doing so requires identifying the climate and precipitation patterns adequate for other biomes, and defining the respective target zones, tree cover targets, quantities and types of trees, carbon gains and economic costs.

Finally, how might forestation in South America take place? Article 6 of the Paris Agreement (2015) sets out how countries can voluntarily cooperate to reach their climate targets,[30] but there are still issues regarding the validation and verification of forest generated carbon credits. Investigations have revealed that some projects overstated their emissions impact, for instance, by protecting forests that were never in danger of being cut down. But reforestation and afforestation projects that grow trees on degraded land is more straightforward, and passive natural regeneration does not take place in areas with low tree cover. Thus, standards regarding tree cover targets and forestation potential may set out the conditions under which carbon removals from reforestation and afforestation are counted towards a carbon credit. Then, our supply curve can show how many carbon credits are expected to be sold at each carbon price, under each set of assumptions.

[30] In particular, Article 6.2 allows countries to exchange mitigation outcomes bilaterally, report their trade, and use them towards their nationally determined contributions (NDCs); and Article 6.4 establishes a new international carbon crediting mechanism for the validation, verification and issuance of carbon credits.

Table A1: Details regarding Points A, B, C, and D on the supply curve in Figure 2.

Point	Model outputs	Calculations
A	Location: Amazon forest of Brazil. Coordinates: (-57.75° long, 1.25° lat). Initial tree cover: 55.0%. Forestation potential: 20.0%. Agricultural activity: Livestock. Land area converted to forest: 66,667 ha. ΔCO_2 absorption rate: 0.73 $MtCO_2$/yr. Total forestation cost: US$ 16.7 MM/yr. Cost per tCO_2 removed: US$ 23.	Trees planted = 20.0× 2 MM = 40.0 MM. Land area converted to forest = $20.0 \times 3,333.333 =$ 66,667 ha. ΔCO_2 absorption rate = $20.0 \times 36,667 = 0.73$ $MtCO_2$/yr (Section 3.3). Land opportunity cost = $131 \times 66,667 =$ \$8.7 MM/yr (Table 1). Tree planting cost = $40,000,000 \times 0.192 =$ \$7.7 MM/yr (Table 2). Forest conservation cost = $4 \times 66,667 =$ \$0.3 MM/yr (Section 4.3). Total forestation cost = \$(8.7 + 7.7 + 0.3 = 16.7) MM/yr. Cost per tCO_2 removed = 16.7/0.73 = \$23.
B	Location: Amazon forest of Brazil. Coordinates: (-49.25° long, -4.25° lat). Initial tree cover: 23.667%. Forestation potential: 51.333%. Agricultural activity: Livestock. Land area converted to forest: 171,111 ha. ΔCO_2 absorption rate: 1.88 $MtCO_2$/yr. Total forestation cost: US$ 56.1 MM/yr. Cost per tCO_2 removed: US$ 30.	Trees planted = 51.333× 2 MM = 102.666 MM. Land area converted to forest = $51.333 \times 3,333.333 =$ 171,110 ha. ΔCO_2 absorption rate = $51.333 \times 36,667 = 1.88$ $MtCO_2$/yr (Section 3.3). Land opportunity cost = $131 \times 171,110 =$ \$22.4 MM/yr (Table 1). Tree planting cost = $102,666,000 \times 0.322 =$ \$33.1 MM/yr (Table 2). Forest conservation cost = $4 \times 171,110 =$ \$0.7 MM/yr (Section 4.3). Total forestation cost = \$(22.4 + 33.1 + 0.7 = 56.2) MM/yr. Cost per tCO_2 removed = 56.2/1.88 = \$30.
C	Location: : Amazon forest of Brazil. Coordinates: (-53.75° long, -14.75° lat). Initial tree cover: 29.333%. Forestation potential: 45.667%. Agricultural activity: Temporary crops. Land area converted to forest: 152,222 ha. ΔCO_2 absorption rate: 1.67 $MtCO_2$/yr. Total forestation cost: US$ 67.4 MM/yr. Cost per tCO_2 removed: US$ 40.	Trees planted = 45.667× 2 MM = 91.334 MM. Land area converted to forest = $45.667 \times 3,333.333 =$ 152,223 ha. ΔCO_2 absorption rate = $45.667 \times 36,667 = 1.67$ $MtCO_2$/yr (Section 3.3). Land opportunity cost = $246 \times 152,223 =$ \$37.4 MM/yr (Table 1). Tree planting cost = $91,334,000 \times 0.322 =$ \$29.4 MM/yr (Table 2). Forest conservation cost = $4 \times 152,223 =$ \$0.6 MM/yr (Section 4.3). Total forestation cost = \$(37.4 + 29.4 + 0.6 = 67.4) MM/yr. Cost per tCO_2 removed = 67.4/1.67 = \$40.
D	Location: Brazilian savanna (Cerrado). Coordinates: (-49.75° long, -20.25° lat). Initial tree cover: 18.0%. Forestation potential: 22.0%. Agricultural activity: Permanent crops. Land area converted to forest: 73,333 ha. ΔCO_2 absorption rate: 0.81 $MtCO_2$/yr. Total forestation cost: US$ 72.1 MM/yr. Cost per tCO_2 removed: US$ 89.	Trees planted = 22.0× 2 MM = 44.0 MM. Land area converted to forest = $22.0 \times 3,333.333 =$ 73,333 ha. ΔCO_2 absorption rate = $22.0 \times 36,667 = 0.81$ $MtCO_2$/yr (Section 3.3). Land opportunity cost = $717 \times 73,333 =$ \$52.6 MM/yr (Table 1). Tree planting cost = $44,000,000 \times 0.438 =$ \$19.3 MM/yr (Table 2). Forest conservation cost = $4 \times 73,333 =$ \$0.3 MM/yr (Section 4.3). Total forestation cost = \$(52.6 + 19.3 + 0.3 = 72.2) MM/yr. Cost per tCO_2 removed = 72.2/0.81 = \$89.

Table A2: Summary statistics for key variables that affect the supply curve (*). Monetary values are in 2020 US dollars.

Variable	**Minimum**	**Median**	**Mean**	**Maximum**	**Std Dev**
Mean annual precipitation (mm/yr)	0	1620	1626	7435	848
Mean maximum cumulative water deficit (mm/yr)	0	268	335	1188	274
Average tree cover (%)	0	27	37	84	29
GPV for temporary crops (US$/ ha)	319	848	992	2457	724
GPV for permanent crops (US$/ ha)	399	2242	2434	6254	1990
GPV for livestock (US$/ ha)	51	126	464	6067	2240
LOC for temporay crops (US$/ ha)	116	118	155	286	66
LOC for permanent crops (US$/ ha)	146	344	322	449	122
LOC for livestock (US$/ ha)	63	94	112	224	58

(*) GPV stands for Gross Production Value; LOC stands for Land Opportunity Cost.

Table A3: Input data and corresponding web-based data sources.

Data type	**Source**
Monthly precipitation data worldwide from Mar/2001 to Feb/2019 at 0.5° resolution (CRU/TS).	Climatic Research Unit, accessed on 2024-02-24 through the link: https://crudata.uea.ac.uk/cru/data/hrg/.
Tree cover data worldwide from Mar/2001 to Feb/2019 at 250-meter spatial resolution (MODIS/VCF).	Moderate Resolution Imaging Spectroradiometer/Vegetation Continuous Fields, accessed on 2024-02-24 through the link: https://lpdaac.usgs.gov/products/mod44bv006/.
Tree densities, carbon gains and CO_2 absorption rates in the tropics.	Crowther et al. (2015), ForestPlots.net et al. (2021), Sullivan et al. (2020*b*), and Mokany, Raison and Prokushkin (2006).
Geographic borders of the Amazon forest.	Brazilian Institute for Space Research, accessed on 2024-02-24 through the link: http://terrabrasilis.dpi.inpe.br/en/download-2/.
Geographic borders of the Atlantic forest and Gran Chaco region.	MapBiomas Project, Annual Series of Land Use and Land Cover Maps (Collections 2.0 and 4.0), accessed on 2024-02-24 through the link: https://code.earthengine.google.com/?accept_repo=users%2Fmapbiomas%2Fuser-toolkit&scriptPath=users%2Fmapbiomas%2Fuser-toolkit%3Amapbiomas-user-toolkit-lulc.js.
Geographic borders of South American countries.	Database of Global Administrative Areas, accessed on 2024-02-24 through the link: https://gadm.org/download_country.html.
Geographic borders of Brazilian states.	Brazilian Institute of Geography and Statistics, accessed on 2024-02-24 through the link: https://www.ibge.gov.br/geociencias/organizacao-do-territorio/malhas-territoriais/15774-malhas.html.
Land opportunity costs for temporary crops, permanent crops and livestock in Brazil.	Obtained by request from the Brazilian Confederation of Agriculture and Livestock (CNA): https://cnabrasil.org.br/.
Tree planting costs.	Kishinami and Watanabe Jr. (2016) and Benini and Adeodato (2017).
Forest conservation costs.	Cunha et al. (2016) and Assunção, Gandour and Rocha (2023).
Gross production values for temporary and permanent crops in Brazil, and the respective planted areas.	Brazilian Institute of Geography and Statistics, accessed on 2024-02-24 through the link: https://www.ibge.gov.br/estatisticas/economicas/agricultura-e-pecuaria/9117-producao-agricola-municipal-culturas-temporarias-e-permanentes.html?=&t=resultados.
Gross production values for livestock in Brazil.	Brazilian Ministry of Agriculture and Livestock, accessed on 2024-02-24 through the link: https://www.gov.br/agricultura/pt-br/assuntos/politica-agricola/valor-bruto-da-producao-agropecuaria-vbp.
Pasture areas for livestock grazing in Brazil.	MapBiomas Project, accessed on 2024-02-24 through the link: https://plataforma.brasil.mapbiomas.org.
Planted and pasture areas for temporary crops, temporary meadows and pastures, permanent crops, and permanent meadows and pastures in South America.	United Nations' Food and Agriculture Organization, accessed on 2024-02-24 through the link: https://www.fao.org/faostat/en/#data/RL.

Table A4: Land opportunity costs in the Brazilian regions and South American countries covered by the forestation target zone (*). Data from 2018-2020 (2020 US dollars).

Geographic unit	**Temp. crops (US$/(ha yr))**	**Perm. crops (US$/(ha yr))**	**Livestock (US$/(ha yr))**
Brazil			
South (S)	286	295	224
Southeast (SE)	118	344	150
Central-West (CW)	118	344	115
Northeast (NE)	174	449	94
North (N)	116	146	63
Argentina	286	295	224
Bolivia	117	245	89
Colombia	116	146	63
Ecuador	116	146	63
French Guiana	116	146	63
Guyana	116	146	63
Paraguay	202	320	170
Peru	116	146	63
Suriname	116	146	63
Uruguay	286	295	224
Venezuela	116	146	63

(*) For South American countries other than Brazil, because of the lack of appropriate cost data, we use the average land opportunity costs for temporary crops, permanent crops and livestock observed in the Brazilian regions closest to their frontiers.

Table A5: Planted, pasture, and potentially forestable areas in the Brazilian states and South American countries covered by the forestation target zone. Values in thousand hectares.

Geographic unit	**Planted and pasture areas in 2020**						**Potentially forestable area ('000 ha)**
	Temp. crops ('000 ha (%))		**Perm. crops ('000 ha (%))**		**Livestock ('000 ha (%))**		
Brazil							
South (S)							
PR	10,741	(80%)	121	(1%)	2,626	(19%)	10,892
RS	9,373	(94%)	159	(2%)	393	(4%)	10,618
SC	1,436	(62%)	76	(3%)	791	(34%)	3,240
Southeast (SE)							
ES	80	(3%)	485	(19%)	1,979	(78%)	3,033
MG	4,640	(18%)	1,193	(5%)	19,320	(77%)	9,134
RJ	76	(4%)	35	(2%)	1,884	(94%)	1,849
SP	8,068	(61%)	795	(6%)	4,353	(33%)	12,456
Central-West (CW)							
GO	6,900	(35%)	41	(0%)	13,015	(65%)	1,520
MS	5,947	(30%)	10	(0%)	13,871	(70%)	13,321
MT	17,150	(45%)	39	(0%)	20,935	(55%)	36,552
Northeast (NE)							
AL	420	(22%)	47	(3%)	1,404	(75%)	710
BA	3,229	(16%)	907	(5%)	15,932	(79%)	3,048
MA	1,700	(19%)	19	(0%)	7,217	(81%)	3,681
PB	337	(21%)	32	(2%)	1,224	(77%)	102
PE	704	(20%)	92	(3%)	2,770	(78%)	573
RN	245	(28%)	82	(9%)	564	(63%)	158
SE	219	(13%)	60	(4%)	1,377	(83%)	523
North (N)							
AC	70	(3%)	12	(1%)	2,192	(96%)	814
AM	102	(4%)	21	(1%)	2,649	(96%)	3,347
AP	36	(13%)	3	(1%)	235	(86%)	2,038
PA	1,364	(6%)	652	(3%)	21,477	(91%)	19,569
RO	722	(8%)	92	(1%)	8,749	(91%)	6,919
RR	84	(8%)	10	(1%)	1,026	(92%)	2,279
TO	1,547	(20%)	5	(0%)	6,113	(80%)	5,344
Brazil (Subtotal)	77,965	(33%)	5,431	(2%)	154,487	(65%)	151,721
Argentina	39,744	(34%)	1,068	(1%)	74,681	(65%)	16,136
Bolivia	3,121	(9%)	251	(1%)	33,000	(91%)	13,724
Colombia	1,850	(4%)	2,505	(6%)	39,504	(90%)	10,006
Ecuador	823	(16%)	1,443	(28%)	2,939	(56%)	2,318
French Guiana	11	(37%)	6	(18%)	14	(45%)	331
Guyana	370	(37%)	28	(3%)	594	(60%)	3,467
Paraguay	4,262	(26%)	90	(1%)	11,985	(73%)	13,332
Peru	909	(4%)	2,262	(10%)	18,800	(86%)	3,529
Suriname	53	(72%)	5	(7%)	16	(22%)	1,298
Uruguay	1,827	(13%)	39	(0%)	12,000	(87%)	5,223
Venezuela	1,950	(9%)	700	(3%)	18,200	(87%)	6,840
Total	132,885	(26%)	13,827	(3%)	366,220	(71%)	227,924

Table A6: Estimates for carbon stock accumulation following reforestation and afforestation

Reference	**Carbon stock accumulation (tC/(ha yr))**	**Notes**
ForestPlots.net et al. (2021)	2.4 (AGB)	Tropical moist forests in South America. Estimate derived from Fig. 6, which shows probability distribution of carbon gains, for average tree age of about 50 years.
Sullivan et al. (2020*b*)	2.4 (AGB)	Tropical forests in South America. Estimate calculated from data package at Sullivan et al. (2020*a*), for average tree age of about 50 years.
Busch et al. (2019)	1.7 (AGB)	Tropical moist forests. Estimate derived from Suppl. Figure 1 for 50 year old trees.
Smith et al. (2016)	3.4 (AGB+BGB)	Mixed types of forests. Forest regrowth over 40 years to maturity.
Griscom et al. (2017)	2.8-5.5 (AGB+BGB)	Maximum mitigation potential in tropical, subtropical and temperate forests. No information about the trees' age.

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