The Supply of Forest-Based CO_2 Removal

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April 2025

Introduction

- Gobal CO_2 emissions continue to rise. Even after a substantial decline, the atmospheric CO_2 concentration will continue to grow and remain high for many years.
- Can we remove CO_2 from the atmosphere? Planting trees — reforestation and afforestation — seems promising.
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- But where to plant trees and at what cost? How much CO_2 can be removed?
- Focusing on South America and using spatially disaggregated data, we estimate a supply curve for atmospheric CO_2 removal.
- The supply curve traces out the marginal cost of removing a metric ton of CO_2 annually over a 50-year period as a function of total forest-based CO_2 removal.

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- So why aren't we planting trees? Instead, we are cutting trees down.

A Note on Deforestation

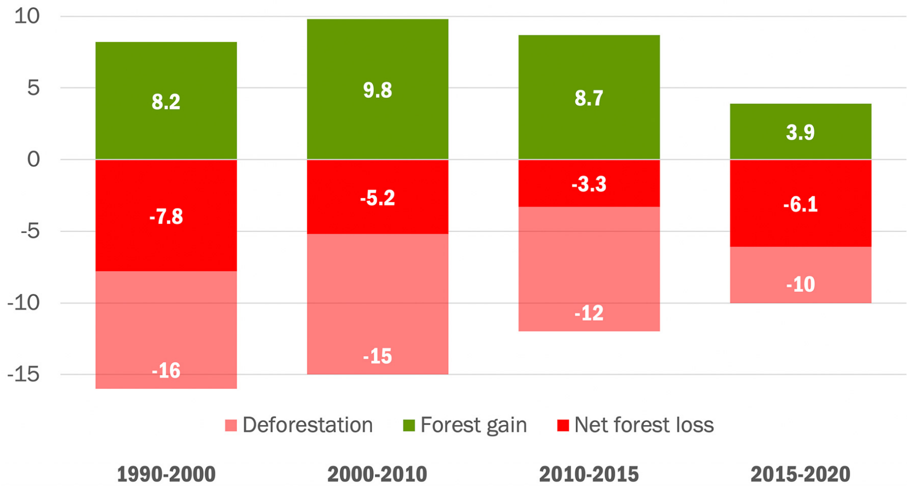

Figure: Net Annual Loss of Forests (million hectares). Source: FAO

A Note on Deforestation (Con't)

- During 2015 to 2020, about 10 million hectares per year of deforestation, partly offset by 4 million hectares of forest gain, for net annual forest loss of 6 million hectares.
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- Why? Because the land is valuable. Can be used for agriculture, cattle grazing, etc. And that's why we don't plant trees.
- What does annual loss of 6 million hectares do to net CO_2 emissions?
  - Each year CO_2 absorption is reduced by $6 \times 10^6 \times 500 \times .02 =$ .06 Gt per year, or about 1 Gt after 17 years.
  - But net emissions increases much more. 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 or is burned.
  - This means a loss of 6 million hectares per year will increase net CO_2 emissions by 0.27 Gt per year, or 1 Gt after 4 years.

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  1. **Opportunity cost of land.** Largest cost component.
  2. **Planting costs.** Must grow seedlings and then plant them with with fertilizer, water, and insect repellent. Later, trees must be pruned and sometimes replanted.
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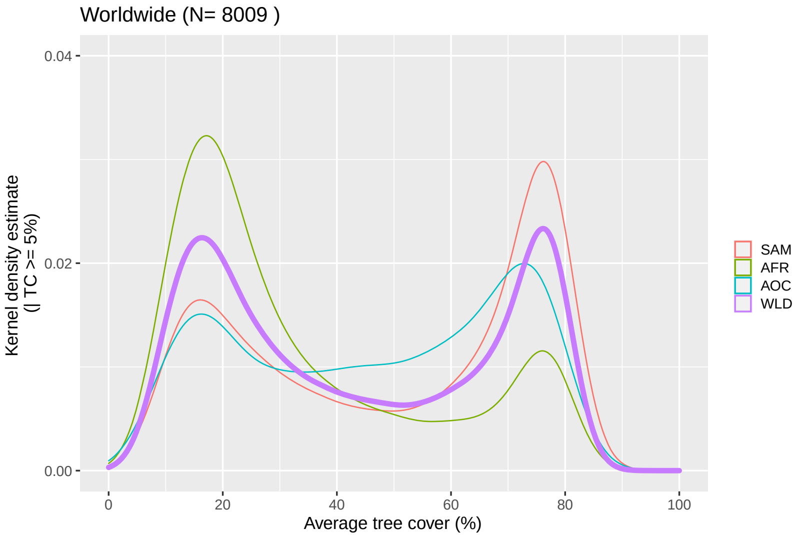
- These costs determine where trees should be planted.
- Only plant where precipitation patterns support forest growth.

How Many Trees to Plant? Up to 75% Tree Cover.

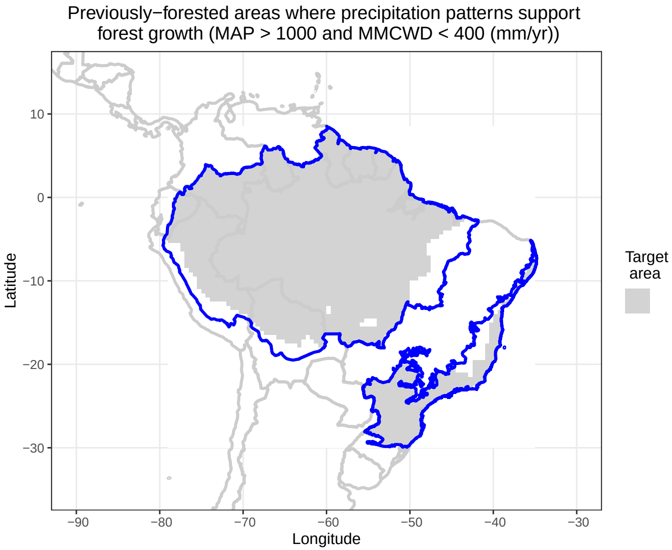


Probability distributions of average tree cover, 2001 to 2018, tropical and subtropical regions worldwide.

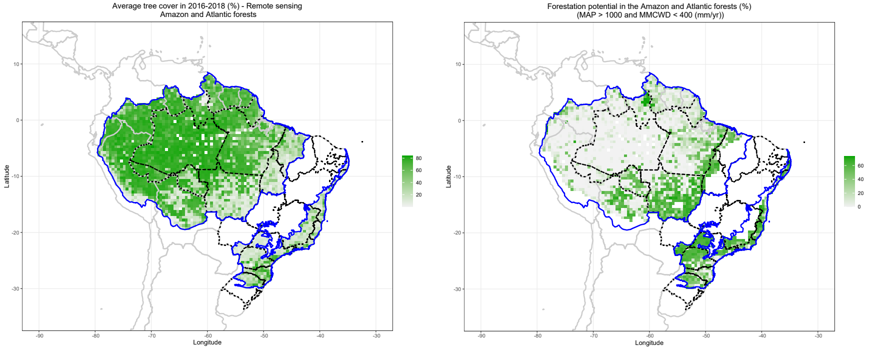
Where and How Much to Plant

- Our data is for South America, at 0.5° longitude-latitude resolution $=$ 250,000 hectares.
- For each $0.5^\circ \times 0.5^\circ$ grid element, data includes:
    - Average tree cover.
    - Average annual precipitation (AP).
    - Average maximum cumulative water deficit (MCWD).
- Plant where current tree cover is $\leq 75\%$, AP > 1000 mm/yr, and MCWD < 400 mm/yr.
- Forest state basin of attraction: 65% to 85% tree cover. So set tree cover target at 75%.
- Forestation potential $= 75\% -$ current tree cover.
- For savannas and grassland, we set tree cover target at 40%.

Forestation Target Zone



Forestation Potential.



Note: Grid element of 250,000 hectares with 75% tree cover is considered “fully forested.” (Savanna and grassland fully forested at 40% cover.) Left panel shows average tree cover 2016–2018; right panel shows forestation potential

Tree Density and CO_2 Absorption.

- Carbon accumulates as both above and below ground biomass (AGB and BGB).
- BGB usually estimated as $0.26\times$ ABG.
  - As trees age, rate of carbon absorption falls.
  - Over 50-years, average AGB absorption $= 2.4$ tons C/ha yr.
  - Multiplying by 1.26, total absorption $= 3.0$ tons C/ha yr $= 3.0 \times 3.67 = 11$ tons CO_2.
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- With 75% upper limit and 600 trees/ha, 1 percentage point increase in tree cover $= 600/75 = 8$ new trees, loss of .0133 ha.
- So for land grid, this means planting $8 \times 250,000 = 2$ million trees over $.0133 \times 250,000 =$ 3,333 ha. Will increase CO_2 absorption rate by $2{,}000{,}000\times 18.33 = 36{,}667$ tons CO_2/yr.

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  - **Maintenance costs.** Mostly this is to protect trees from illegal logging. We use Brazilian expenditures on forest conservation.

Land Opportunity Costs (2020 US$/(ha yr))

Geographic unit	Temp. crops	Perm. crops	Livestock
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
Guyana	242	304	131
Paraguay	421	666	353
Peru	242	304	131
Uruguay	596	614	467
Venezuela	242	304	131

Tree Planting Costs

Biome and forest recovery technique	Present values ($/ha)*	($/tree)	Annualized $/(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 up to 75%	2,700	5.87	0.322
Savannas and grasslands:			
Total planting up to 40%	1,440	8.00	0.438

*For areas of savanna and grassland, tree cover target is 40%, so tree planting cost per hectare is (40/75) of the value for areas of forest, where target is 75%.

Building the Supply Curve

- For each land grid in the target zone, we consider increasing its tree cover to target level (75% or 40%).
- To determine grid's land opportunity cost, must identify which agricultural activity will be performed. Areas now used for temporary crops, etc. are not georeferenced.
- But for each Brazilian state and SA country we know percentage now used for each activity. Use this to estimate forestable area from each activity, and land opportunity cost for each grid.

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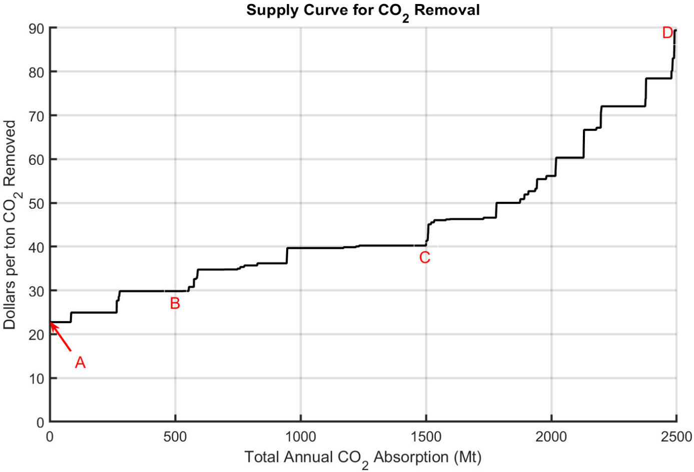
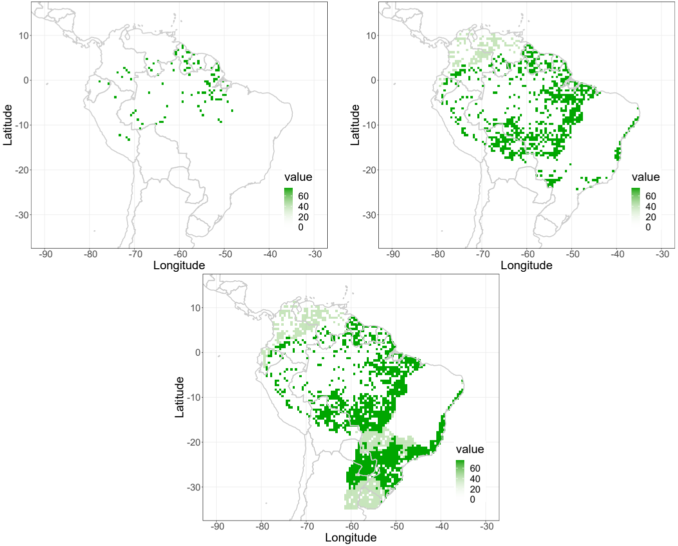
1. Start with all grid elements within the target zone. Economies of scale, so remove those with forestation potential below 10%.
2. Assume each grid element is being used for agricultural activity with minimum land opportunity cost.
3. Sum current minimum land opportunity cost and tree planting cost to get current minimum total forestation cost.
4. Pick grid element with minimum total forestation cost per ton of CO_2 annually sequestered. Repeat to build up curve.

Supply Curve for CO_2 Removal



Point A, in Brazilian Amazon, is lowest cost ($23/ton) because of plentiful rainfall and low planting and land opportunity costs. At Point B, also in Brazilian Amazon, tree planting costs are higher. At Point C (Brazilian Amazon), land opportunity costs are higher so cost of removing CO_2 is $40 per ton. Point D, in Brazilian Cerrado, is savanna, with lower forestation potential and higher land opportunity costs, so cost of removing CO_2 is $90 per ton.

Land Grid Selection



Land Grids Selected for Forestation: First 100; First 880; First 1761 (All).

Sensitivity

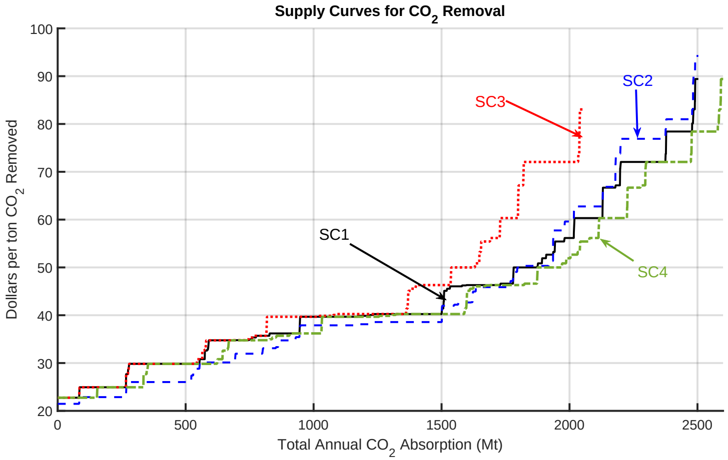


Figure: Alternative Supply Curves. SC1 (black) is the base case curve. SC2 (blue) uses a 2.5% discount rate (instead of 5%). SC3 (red) is supply curve that only includes areas previously forested. SC4 (green) includes all land grids with *any* forestation potential.

Cost of Forest-Based CO_2 Removal.

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- That would cost about $10 \times 90 =$ \$900 billion annually if payments were \$90 per ton, or $4 \times 110 =$ \$440 billion (less than 0.5% of world GDP) if payments were at marginal cost.

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    - We have ignored other benefits from forestation — e.g., water recycling and erosion control — which have external economic value, and from a policy perspective affect the supply curve by reducing the "full" marginal cost of CO_2 removal.
    - How might forestation occur? Article 6 of the 2015 Paris Agreement sets out a credit-based framework, but validation of carbon credits is problematic: Some projects clearly overstate their emissions impact.