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Carbon prices and reforestation in tropical forests

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Foreword

The 23rd BIS Annual Conference took place in Basel, Switzerland, on 28 June 2024. The event brought together a distinguished group of central bank Governors, leading academics and former public officials to exchange views on the theme "Navigating uncharted waters: opportunities and risks for central banks". The papers presented at the conference are released as BIS Working Papers, nos 1222, 1223, 1224 and 1225.

BIS Paper no 150 contains remarks from the closing panel on "Revisiting the last decade of monetary policy", by Michele Bullock (Reserve Bank of Australia), Pablo Hernández de Cos (Bank of Spain), Thomas Jordan (Swiss National Bank) and Sethaput Suthiwartnarueput (Bank of Thailand).

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Carbon prices and reforestation of tropical forests

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Abstract

I discuss recent research joint with J. Assunção, L. P. Hansen and T. Munson that shows that reforestation in tropical forests has great potential for carbon capture. This research accounts for the dynamics of carbon accumulation in tropical forests and uses a rich data set from the Brazilian Amazon, which encompasses 60% of the largest tropical forest on earth. Specifically, we document that (a) in a business-as-usual scenario, the Brazilian Amazon would emit 17 Gigatons of CO2e in the next 30 years and (b) with transfers to Brazil of $25 per net ton of CO2e captured, optimal land use would imply substantial reforestation in areas currently used for low-productivity cattle ranching, yielding 15 Gigatons of CO2e capture in 30 years. Transfers of $25/ton compare very favorably with other CCS schemes or with prices in carbon trading-markets. The total change in trajectory, 32 Gigatons, is large relative to the carbon budget estimated to avoid 50% odds of exceeding 1.5℃ warming. I discuss structures that would give incentives for Brazil not to abandon carbon-capture in the future. I also briefly summarize work in Araujo et al. (2023) that shows that forest degradation in the Amazon generates substantial negative externalities to other portions of the forest. Keywords: climate change, carbon emissions, carbon capture, reforestation, tropical forests. JEL codes: Q01, Q23, Q54, Q57.

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[*] Non-technical background paper based on “Carbon prices and forest preservation over time and space in the Brazilian Amazon” joint with J. Assunção, L. P. Hansen ad T. Munson, and prepared for the 23rd BIS Annual Conference. I thank Juliano Assunção for suggestions and Patricio Hernandez for very able research assistance. This research was supported by Columbia Climate School.

1 Introduction

In this paper, I discuss recent research joint with J. Assunção, L. Hansen and T. Munson that uses data on the Brazilian Amazon Forest, which comprises 60% of the largest tropical rainforest in the world, to examine the potential benefits and costs of reforestation as part of the solution to avoid excessive global warming. Tropical rainforests are forest ecosystems located between the tropics and characterized by high levels of rainfall, an enclosed canopy and high carbon-density. [1]

Carbon stored in the Amazon, if released, would produce approximately 600 Gigatons of CO_2, [2] equivalent to more than 15 times the estimate by the International Energy Agency of global energy-related emissions during 2023.[3] As other tropical forests, the Amazon plays a crucial role in regulating local and regional precipitation and temperature and are thought to have a large impact in global climate.[4] The forest "recycles" rain and trade-winds carry moisture to areas southwest, affecting economic activities, including agricultural productivity in the crucial *Cerrado* region.[5] In addition, the Amazon is incredibly bio-diverse; it holds approximately 10% of the world's vertebrate and plant species.[6]

Unfortunately, the Brazilian Amazon has experienced deforestation that already reached 15% of its area in 2017. If we remain on this business-as-usual trajectory, deforestation would exceed 22%, creating a scenario that could yield as described in Flores et al. (2024) "unexpected eco-system transitions and potentially exacerbate regional climate change." In addition, deforestation and degradation lower water recycling and causes loss of moisture in areas down-wind, creating a cascading effects that doubles the impact of the initial damage.[7]

Deforestation has made the Brazilian Amazon a substantial outlier when placed on a plot of countries' emissions per-capita *vs.* GDP per-capita.

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[1] The Congo forest, the second largest tropical rainforest, covers an area of approximately 290 million hectares mostly in DRC and the Republic of Congo. Other smaller major tropical rainforests include the Sundaland forest in Indonesia and Malasia and the Australasian forest in Indonesia and Papua New Guinea. In this paper, I will often refer to tropical rainforests as tropical forests, although this is not exact.

[2] Flores et al. (2024)

[3] I use the term CO_2 is used to refer to extended CO_2, which accounts also for other greenhouse gases, such as methane.

[4] Flores et al. (2024).

[5] Araujo (2023).

[6] Amazon Assessment Report 2021. https://www.theamazonwewant.org

[7] Araujo et al. (2023)

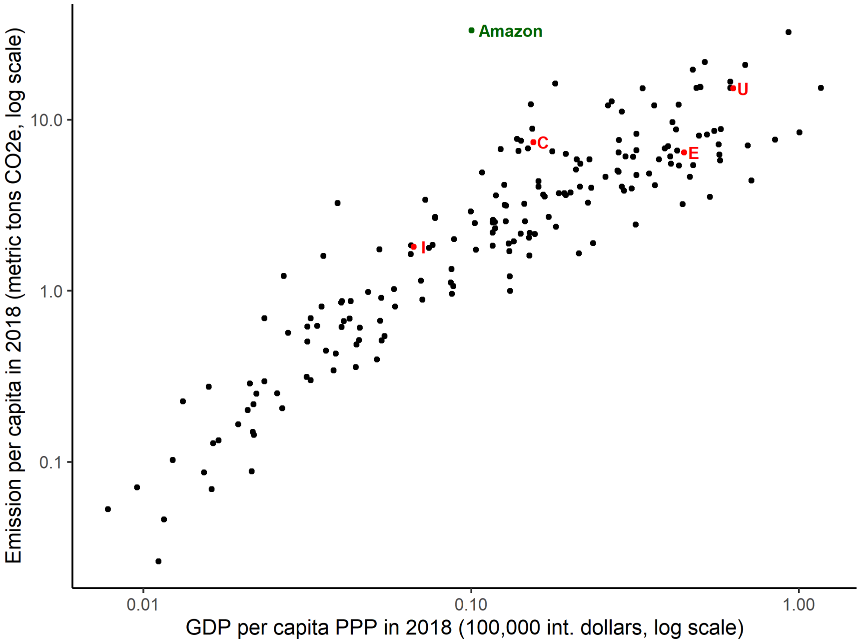

Figure 1: Each dot represents a country in 2018, except for the European Union and the Brazilian Amazon. Highlighted letters stand for (C)hina, (I)ndia, (E)uropean Union, and (U)nited States. Sources: World Bank Data, downloaded on March 2021; Fatos da Amazônia 2021 (www.amazonia2030.org).

More than 85% of deforested and not yet abandoned areas has been dedicated to beef cattle (Mapbiomas- www.mapbiomas.org), with very low productivity. The goal in this case is not necessarily to run a profitable cattle farm, what may be impossible, but mainly to establish property rights in public land, by establishing continuous possession, hoping to benefit from the next amnesty law. It is therefore not surprising that the strategy of replacing the forest with cattle failed to generate reasonable standard of living for the local populations. Median wage in agriculture in the Amazon region are below the already low Brazilian minimum wage and the overwhelming share of workers are informal. The Amazon has some of the lowest indicators of health, education, sanitation and communication in Brazil.

The substantial deforestation of the Amazon is truly an ecological and economic disaster but currently it offers an opportunity. In the Amazon, trees can store the equivalent of 500-550 tons of CO_2 on the average hectare. Because land productivity is low and typically declines over time, 20% of deforested areas are currently abandoned and experiencing large-scale reforestation, highlighting the opportunity for natural forest restoration.[8]

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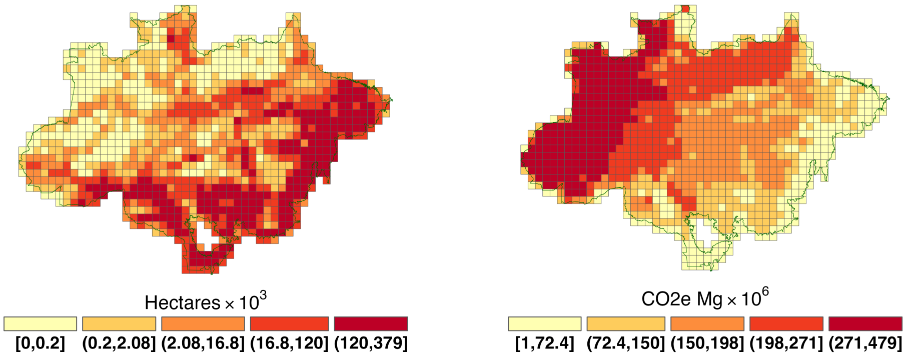
[8] There are currently 6.5 million hectares that have been reforesting for at least 6 years, including areas in the "arc of deforestation" in Southern and Eastern Amazon that displays the highest rate of deforestation.

2 Carbon prices and Amazon forest reforestation

In Assunção et al. (2023b) we investigate the potential social gains of preservation and reforestation in the Brazilian Amazon through the lens of a a dynamic and spatial model that considers the trade-off between cattle production and carbon capture. The model is dynamic and quantitative and uses detailed spatial information from multiple data sets. We account explicitly for the dynamics of carbon accumulation in the forest - a crucial ingredient to provide credible measures of the potential role of preservation and reforestation in the Amazon forest to moderate global warming at different horizons. The data document large cross-sectional variability in cattle farming productivity and in the potential absorption of carbon in the Brazilian Amazon. To account for this variability, the model considers a detailed division of the Brazilian Amazon into various sites.

Figure 2: Initial values for agricultural area and carbon stock



(a) Agricultural area

(b) Carbon stock

Figure 2 shows the initial land allocated to agriculture and the initial stock of absorbed carbon across sites.[9] Figure 3a shows how carbon sequestration capacity varies across the different sites, and Figure 3b does the same for the productivity of cattle-ranching.[10] The correlation between these two productivity measures across sites is $-.35$. Thus, while cattle-ranching productivity and carbon absorption capacity are negatively correlated, this relationship is imperfect.

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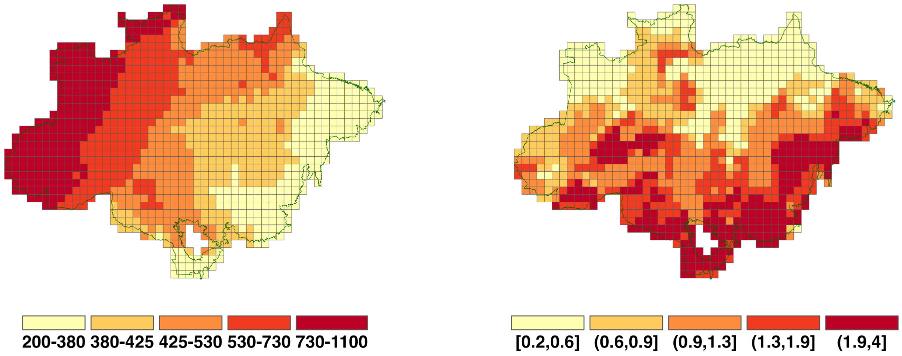
[9] This figure, as other figures that follow, comes from Assunção et al. (2023b)

[10] Since the last agricultural census was done in 2017, here and in what follows we set 2017 as the starting date.

Figure 3: Carbon sequestration and ranching productivity



(a) Carbon sequestration capacity (b) Cattle-ranching productivity

The paper also considers the impact of uncertainty concerning the future evolution of cattle prices and the fact that value of crucial parameters such as the productivity of cattle production and potential for carbon capture are known imprecisely - what is sometimes referred as "deep uncertainty".

We first use the model to elicit an estimate of the "shadow price" of CO_2 emissions revealed by the deforestation that actually occurred from 1995 to 2008. The year 1995 is the first date at which we have reliable price data on cattle prices.[11] In 2008, the Amazon Fund was established with financing mostly for the Norwegian and German governments. The funding was a pay-for-performance scheme based on an emissions price of \$5 per ton of CO_2.

We employed this estimated shadow price per ton of CO_2 to make forecasts that capture "business-as-usual." This shadow price is an implicit measure of the value for Brazilians of the "forest services" provided by preserved areas, including carbon accumulation. Other services would include the value of production that occurs without destroying the forest.[12] Although this shadow price depends on the particular version of the model we use, they coalesce around \$7 per ton.

We then considered the effect on future preservation and reforestation of adding different amounts of $\$b$ for every **net** ton of CO_2 captured to the shadow price.[13] The variation in shadow prices across models, actually make predicted future trajectories **less** dependent on the model variation chosen. A model that is more aggressive on deforestation needs a higher shadow price than that of a less aggressive model to explain the same observed deforestation.

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[11] 1995 marks the establishment of the Real plan that finally ended a period of very high and volatile inflation, making recorded prices less trustworthy before.

[12] *i.e.*, forest products like natural rubber, nuts, and açaí, sustainable timber, tourist services.

[13] Thus there is no reward for pure preservation.

Thus for a fixed transfer level b per ton of CO_2, a planer using the more aggressive model would be considering a higher total price for captured carbon, bringing the future trajectory closer to the trajectory that would obtain if the planer would use the less aggressive model.

Of course, Brazil would have to find it advantageous to sign an agreement to commit to receive (pay) \$b dollars per unit of CO_2 captured (emitted). For instance, as Figure 4 below shows, in the business as usual scenario, Brazil would substantially increase the deforested area, specially in the next twenty years. A very small b would lead to a small change in the optimal trajectory for Brazil, but if agreed to, it would imply on net payments by Brazil. Brazil would clearly be better off by declining to sign an agreement that specifies a small amount per ton of net CO_2 captured.

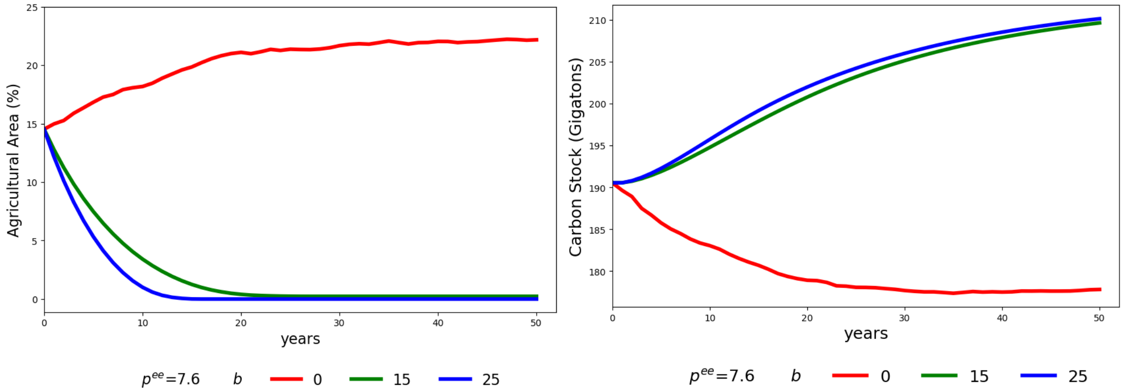

Figure 4: Agricultural area and carbon stock evolution.

As Figure 4 shows, with “business-as-usual” (zero transfers), the optimal choice involves an increase in the agricultural area from 15% to more than 20% of the biome. This increase may actually cause sufficient deforestation for the hydrological cycle of the Amazon to degrade to the point of being unable to support rain forest ecosystems in certain areas of the current biome. (Flores et al. (2024)). The predicted trajectories are much different with additional payments per ton of \$10, \$15, \$20 or \$25. Figure 5 reports the trajectories over time of the transfer payments for $b = \$15$ and $b = \$25$. The peak payments occur after about 12 years for both values of b. As expected, transfer payments for $b = \$25$ are much larger that the corresponding payments for $b = \$15$.

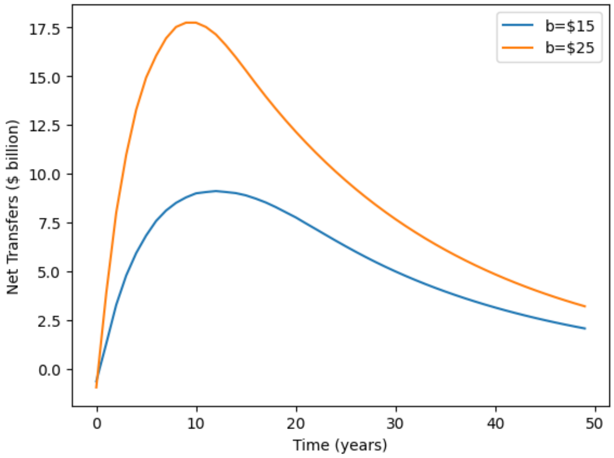

Figure 5: Evolution of transfer payments for $b = \$15$ and $b = \$25$.

The transfer payments result in a substantial decrease in agricultural area and a corresponding increase in forested area. Table 1 gives the discounted value to the planner of a commitment to receive $\$b$ of net transfers for each ton captured of CO_2. It also gives a decomposition of this present value. "Forest services" are measured at the calculated Brazilian shadow price for zero-transfers. Net transfers to Brazil are reported separately. Even transfers of $10 per ton are enough to compensate the losses of agricultural output, but the largest contributor to the gains is the increase in forest services. The larger transfer of $25 per ton of net captured CO_2 almost doubles the value for the planner - a net gain of $224 billion. This net gain is composed of a loss of $354 billion in the value of cattle output,[14] which is more than compensated by $351 billion in transfers and a net gain of $246 billion in forest services. Adjustment costs, the costs of changing land-use, are a small part of the story.

Table 1: Present-value decomposition

b ($)	Agricultural Output Value ($ billion)	Net Transfers ($ billion)	Forest Services ($ billion)	Adjustment Costs ($ billion)	Planner Value ($ billion)
0	372.86	0.00	-139.75	7.69	225.42
5	133.26	30.43	46.26	5.64	204.31
10	57.72	116.05	88.20	11.73	250.24
15	33.29	197.21	99.92	17.63	312.78
20	23.60	274.68	104.38	22.49	380.16
25	18.69	350.92	106.68	26.63	449.67

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[14] We use a measure of full output as value added. Thus, we have exaggerated the loss of agricultural output.

Table 2 displays the total effect of transfers per ton of net CO_2 captured in the first 30 years. For the zero-transfer case, the planner chooses deforestation that induces carbon emissions of 18 billion tons per year in the first 30 years. The table uses this baseline in featuring the "effective cost." We calculated this as the ratio of discounted net transfers to the difference between the net carbon captured and the corresponding baseline value when $b = 0$. With transfers of \$15/ton, optimal management induces capture of 7.2 billion tons by year 30. The effective costs per ton is \$4.9, one-third of the amount paid per net-ton captured. With transfers of \$25/ton, there are modest increases in captured carbon, generating effective costs that almost 80% higher, but again with an effective price close to one third of the transfer payments per net-ton captured. The results in Table 2 illustrate the large gains from trade from instituting a contract that pays Brazil per net ton of CO_2 captured.

Table 2: Transfer costs – 30 years

b (\$)	Net captured emissions (billion tons of CO2e)	Discounted net transfers (\$ billion)	Discounted effective cost (\$ per ton of CO2e)
0	-17.75	0.00	–
25	14.92	284.48	8.71

As already hinted by Figure 5, Table 3 below shows that almost 2/3 of the 30 year gains-from trade effect occurs in 15 years. In particular, the difference between the net carbon captured when $b = 25$ and the corresponding baseline value when $b = 0$ for the first 15 years exceed 20 billion tons of CO_2, at an almost identical effective cost.

Table 3: Transfer costs – 15 years

b (\$)	Net captured emissions (billion tons of CO2e)	Discounted net transfers (\$ billion)	Discounted effective cost (\$ per ton of CO2e)
0	-12.09	0.00.	–
5	2.39	9.91	0.68
10	5.18	43.50	2.52
15	6.64	83.96	4.48
20	7.55	127.72	6.50
25	8.13	172.50	8.53

Figure 6 exhibits the initial occupation and the distribution of land allocation over 30 years for transfers per ton = \$0, \$10, and \$25. Figure 6 shows that for the case of transfers that exceed \$10 per ton of net emissions, the area of the biome that is occupied by cattle farming after 30 years would be substantially reduced in comparison to the 2017 allocation. This is in sharp contrast to what transpires in the $b = 0$ business-as-usual specification in which agricultural production becomes quite intense in South-Eastern sites.

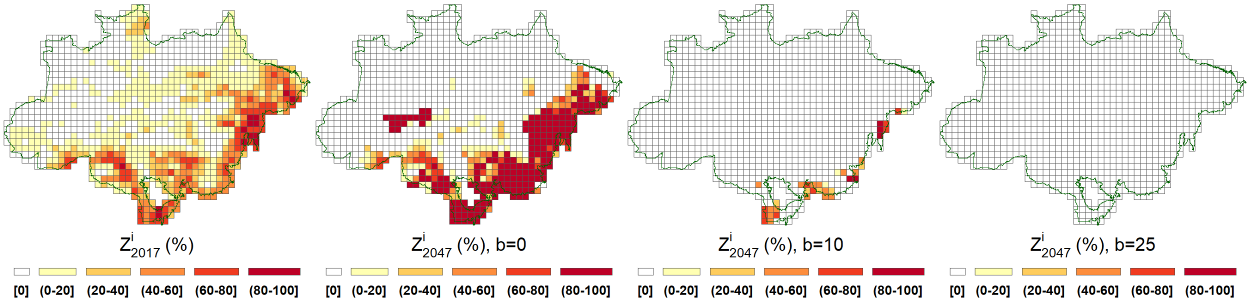

Figure 6: Agricultural area changes after 30 years.

3 Implementation

At least since 1988, most deforestation in the Amazon by private actors has been illegal, though often tolerated by the authorities, who ignored private appropriation of public lands and land assigned to native people. Unless government tolerance to illegal land-invasion in the Amazon ceases, public or private carbon-capture projects would be subject to risk of deforestation by future land-grabbers. Previous experience however show that it is feasible to severely limit illegal deforestation. Deforestation was successfully contained by the DETER plan implemented in 2006 which unfortunately was abandoned in the middle of the next decade. DETER used satellite information to find violations and send agents that would apply penalties.[15] Assunção et al. (2023a) estimates that DETER reduced deforestation rates by 85% saving 10 billion tons of emissions in a decade, at a cost of less than \$1/ton. The low estimated cost is a result of the scale economies associated with surveillance using satellite base systems.

Although with transfers of \$25 per ton, carbon-capture would generate enough aggregate payments to compensate landowners for their loss of future income from cattle farming, the price of land also reflects the probability of future roads or other public investments that would increase the payoff of nearby land. To make the carbon-capture scheme financially feasible, the government would need to make commitments that signal to current land-occupiers that they would not benefit from such projects.

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[15] In addition, this information was often used to apprehend and destruct the heavy machinery that is necessary for deforestation in the Amazon.

Due to the intense humidity, fires do not occur naturally in tropical rainforests, in contrast to temperate forests. However, repeated fires started to renew pasture frequently spread and cause forest degradation, and eventually lead to large forest fires.[16] A larger contiguous protected area would have proportionally less contact with unregulated areas at the border and thus be more immune to accidental fires. In addition to these "edge effects", forest in "fragments", areas of less than 100km^2, display deteriorated carbon accumulation dynamics.[17] This implies that a successful restoration project of the forest must be done at scale.

The need for effective enforcement and scale favors assigning responsibility to the Brazilian Federal Government. An additional reason, is the distinction between preservation and reforestation that is often made in policy discussions. In the model in Assunção et al. (2023b), Brazil would be paid for net-capture, what is equivalent to taxing forest destruction and paying for reforestation. The reason Brazil would accept to be taxed for forest destruction in its territories, provided b was large enough, is that payments for CO_2 capture and gains from forest services would more than compensate the forgone gains from deforestation. Obviously this mechanism would not be effective with legal private-owners of land that are still relatively untouched. However, Brazilian forest code requires that any deforestation obtains a federal license and the government could instead pay the owners using funds from receipts of carbon-capture sales.[18]

In turn, the monetary scale of the scheme, involving payments that exceed in some years 17 billion dollars, make it unlikely that it could be financed by the private sector. In addition, Brazil would need guarantees that once cattle-farming is abandoned and land is dedicated to restoration, payments for future carbon-capture will happen. This requires that buyers be countries or group of countries with excellent credit ratings, perhaps inter-mediated by international organizations such as the World Bank.

3.1 Incentives to defect

Table 1 shows that the planner would agree to sign an agreement to receive (pay) $b = \$25$ dollars for each ton of CO_2 captured (emitted) in the Brazilian Amazon. However, as see in Figure 5, the flow of payments falls after a peak and tends towards zero. This is natural, since mature forests reach an equilibrium. Figure 7 compares at each point in time up to 50 years, the value of continuing with the optimal path given transfers of \$25 per ton with

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[16] "In the extensive beef-cattle production, annual or biennial fires are commonly applied to stimulate grass regrowth in the dry season when forage is in short supply. Most cattle ranchers do not make firebreaks and the fire spreads to large areas". Pivello (2011)

[17] *e.g.*Cochrane and Laurance (2002)

[18] A similar issue would arise for countries with more preserved tropical forests. These countries would have to be compensated for preservation, since they would have little emission-capture to sell.

the value of defecting and facing $b = 0$. For $t = 0$ we know that Brazil would not defect but defecting becomes advantageous after 44 years. However the maximum present value of the difference for theb firstv50n years, M, equals \$8.2 billion. If transfers are \$30 per net captured ton, then $M = 4.9$ billion.

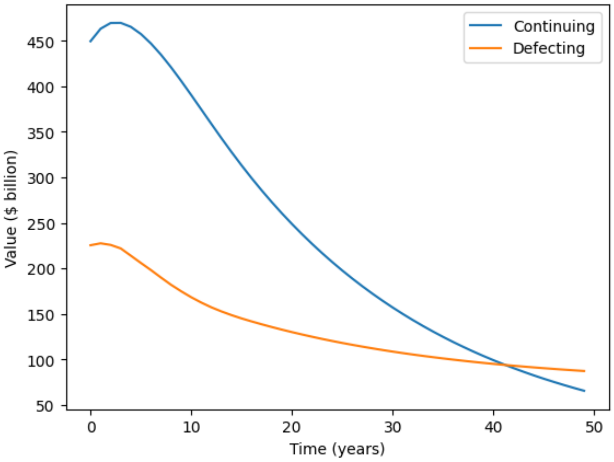

Figure 7: Value under $b = \$25$ transfer scheme vs value of defecting.

There are at least two ways to avoid defection. One, a carrot, would involve buyers establishing a fund with a value of M (8.2 billion for the case of \$25/ton transfers) at time 0. The fund would be payable to Brazil if aggregate changes in land-use did not deviate substantially from the target until $t = 50$.[19] Given the estimates in Table 2 this would amount to adding 55 cents to the effective cost per/ton. Alternatively, one could consider a stick: Brazil would be required to issue a bond with an initial value of M that would accumulate at the fixed real interest rate, which becomes due if, and only if, a substantial deviation in aggregate planned land-use is observed at some time up to 50 years. The carrot or stick could be complemented by a boycott of agricultural goods produced in the Amazon, if Brazil defects.

There is also a problem concerning the commitment of buyers. Brazil would change use of cattle-grazing areas, in the expectation of future income from carbon-capture. Changes in technology or politics could induce paying countries to prefer not to buy in the future the carbon-capture obtained. Again this could be solved by the use of contingent bonds, now issued by purchasing countries.

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[19] Conditioning on area would avoid Brazil's exposure to shocks in carbon absorption capacity that may result from global warming.

4 Spatial amplification of forest degradation

In tropical forests trees recycle humidity back to the atmosphere.[20] Thus rainfall generates tree transpiration which recharges atmospheric humidity. Trade-winds move humidity causing rain in downwind direction and generating "flying rivers" that are responsible for between 30 and 40% of the total rainfall in the Amazon. Thus in addition to its local-impact, human induced forest-degradation in the Amazon is likely to cascade in the south-western direction of the trade-winds in the region. In Araujo et al. (2023) we use panel data technique and high resolution data-sets on the state of the forest[21] and on wind speed and direction to estimate the **causal** effect of degradation in the Amazon forest. We estimate that, on average, the presence of cascading effects mediated by winds in the Amazon doubles the impact of an initial damage. However, we find heterogeneity in this impact. While damage in some regions does not propagate, in others amplification can reach 250%.[22] Regions with high propagation multipliers demand special attention from policy-makers. We also identify regions that are particularly sensitive to degradation in other area of the Amazon biome. Since wind patterns do not respect borders, these effects can be transnational. For instance, degradation of the forest on the Brazilian state of Rondonia, a region that has suffered some of the highest rates of deforestation in the recent past, results in degradation of portions of the Bolivian Amazon.

The presence of these externalities makes deforestation more costly and reforestation more beneficial than the values obtained in Assunção et al. (2023b). These externalities make even more dramatic the difference between the "business as usual" outcome and the results when sufficient transfers of per net ton of CO_2 are arranged.

5 Additional remarks.

5.1 Reforestation versus other carbon capture and storage schemes.

Carbon capture and sequestration schemes (CCS) in the US, as well as other countries, involve predominantly capture for use to enhance the yield from old oil/gas reserves (EOR). The US is the largest deployer of CCS projects. The Congressional Budget Office reported in 9/2023 that the fifteen CCS facilities then operating in the United States had the capacity to capture only 0.4 percent of the nation's total annual CO_2 emissions. 95% of the capacity

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[20] Salati et al. (1979).

[21] The degradation state of any forest-site is measured by its Leaf Area Index (LAI), the ratio of the total (one-sided) area of leaves in a site to the site's area.

[22] Since Araujo et al. (2023) only account or spillovers mediated by winds, the multiplier of 2 should be seen as a lower bound.

provided by these fifteen facilities was used for EOR. An additional 121 CCS facilities were under construction or in development at that date. If these facilities are completed, US carbon capture and sequestration annual capacity would amount to 165 million tons or 3 percent of current annual CO_2 emissions.

Once we consider the extra CO_2 emitted by the additional production of carbon based fuel, it is not clear how much net capture of CO_2 each of these facilities yields, but Occidental Petroleum, currently developing large carbon removal facilities projects in Texas, uses EOR to sell ”net-zero oil [sic]”. It is not by accident, but by design, that CCS projects increase fossil fuel production. A joint report on the 2010 symposium on the Role of Enhanced Oil Recovery (EOR) in Accelerating the Deployment of Carbon Capture and Sequestration (CCS), co-hosted by the MIT Energy Initiative (MITEI) and the Bureau of Economic Geology at the University of Texas (UT-BEG) states that “The motivation ... lies with the convergence of two national energy priorities: enhancement of domestic oil production through increased tertiary recovery; establishment of large-scale CCS as an enabler for continued coal use in a future carbon-constrained world. These security and environmental goals can both be advanced by utilizing the carbon dioxide (CO2) captured from coal (and natural gas) combustion for EOR.”[23] Under IRA, U.S. 45Q credit for EOR CCS is $60/ton for facilities that start construction before 2033, and pay prevailing wages for the first 12 years of operations.

CCS projects have long-term risks that private companies cannot or are not willing to hold. In fact, limited liability implies that indemnification for loss is only possible up to the value of the firm’s assets (Gollier (2005). This explains why long term liability for leaks in CCS are often transferred to governments *ex-ante*, even for projects undertaken by well-funded firms.[24]

5.2 Emissions price-dispersion

Figure 8 below shows April 2023 prices reported by the World Bank for direct carbon pricing instruments and carbon markets around the world, which exceed of at least $25 - the amount we estimate would produce notable carbon capture via reforestation in the Brazilian Amazon. Notice that some of the largest programs, such as the EU ETS, display prices that are multiples of $25.

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[23] Initiative (2010).

[24] For instance, the Australian Commonwealth and Western Australia state agreed to take over liability of Gorgon CCS project from Chevron and partners that include Shell and ExxonMobil after closing of project.

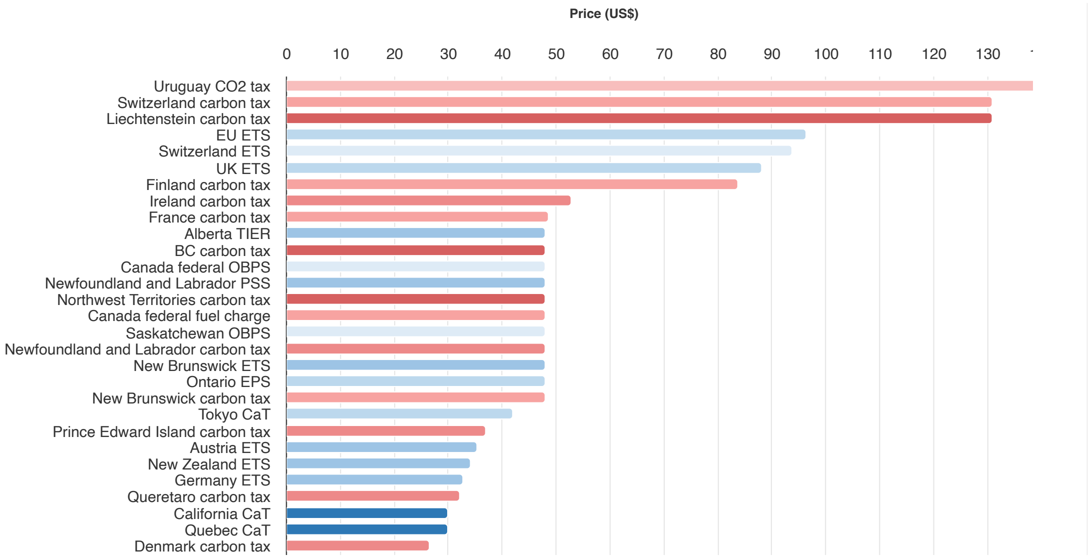

Figure 8: From World Bank's carbon pricing dashboard. Prices of April 2023.

Since a ton of additional CO_2 emitted (captured) anywhere has the same effect on climate change, basic economics indicates that the implicit carbon tax (subsidy) should also be invariant to location. In fact, this is the rationale behind tradable-emissions schemes such as the EU ETS.

Currently, European firms may use imported inputs, such as US natural gas or Chinese PV panels to satisfy EU requirements, but are not allowed to obtain credit for paying for carbon capture abroad.[25] Common objections to purchase of non-EU carbon capture credit include the argument that CCS is an infant industry that needs protection. In general, if governments want to help develop local CCS or other technologies that though inefficient today show promise for the future, they should give additional subsidies to developers of technologies that though inefficient today may show promise for the future, but there is no obvious reason why the subsidy should be proportional to current output as tariffs or prohibition of imports do. Another objection is that accepting non-EU carbon capture credit would export CO_2 emissions. In the case of net-payment schemes such as the one discussed here, this is not a concern. Brazil would face a loss for $12,500 per hectare deforested.[26] Currently, Amazon deforestation is responsible for close to 50% of Brazil's emissions and at $25/ton the country would reduce almost immediately its own emissions by 40-50%, what exceeds EU goal of reducing its own emissions by 30%. As Figure 4 shows, carbon capture

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[25] Since the European carbon adjustment mechanism (CBAM) focuses on specific goods, imported PV panels or natural gas are not currently covered and thus exempt from EU carbon pricing. In addition, the carbon footprint of production and transportation of natural gas is substantially underestimated (Alvarez et al. (2018).

[26] This does not apply for the isolated reforestation projects paid by NGOs or private companies now prevalent. There is no guarantee that inputs used for deforestation would not simply move elsewhere.

in reforested areas would further reduce net emissions on a relatively short time horizon.

Of course, in the case of carbon-capture, the subsidy must also reflect the resilience of the capture. As we argued above, a properly designed scheme for carbon-capture in tropical forests can be made very resilient. In addition, establishing compensation for carbon capture requires establishing an accounting system that credits only once any carbon capture.

The politics of fighting climate change has resulted in programs with very different carbon prices, and steps that unify, even if partially, these markets would increase efficiency in combating global warming.

5.3 Involving the private sector

Although the scale of carbon-capture in the Amazon requires that governments bear the final responsibility for carbon-capture and payments, the is also a role for the private sector. On the Brazilian side, active regeneration may be more efficient than the natural regeneration Assunção et al. (2023b) assumes in specific areas. Production compatible with the forest, including natural rubber, nuts, and açaí, should continue to be conducted by private actors. On the buyers side countries should allow private firms to satisfy part of their emissions goals by purchasing credits in the Amazon, increasing the supply of funds to the Amazon. This would lower the current dispersion of implied carbon taxes and, as argued in Section5.2, increase efficiency in the fight against global warming.

6 Conclusions

Simulations reported in Table 2 suggest that international carbon payments of \$25 USD/ton can reduce emissions by 32 billion tons of CO_2 equivalent emissions in the next 30 years. Fifteen billion tons represent carbon capture by natural regeneration, for which Brazil will receive payments, and the rest represents avoided emissions from deforestation that would happen in the "business-as-usual" scenario. As shown in Figure 5, carbon capture in this \$25/ton scenario is front loaded but the average CO_2 capture over the 30-year period would amount to 500 million tons. Griscom et al. (2017) estimates that nature-based solutions such as forest restoration, avoided land conversion, forest management and other practices have the potential of capturing about 11.3 billion tons of CO_2 per year globally, with costs no greater than \$100 USD/ton. Our simulations of transfer costs (Table 2) suggests that optimal management of the Brazilian Amazon could make a substantial contributions at a much lower effective cost. Of course, given the alternative costs of current CO_2 capture or emission savings schemes there is plenty of space for bargaining over transfers per ton of

CO_2 captured by reforestation of natural forests.

Simulations in Assunção et al. (2023b) ignore the loss of biodiversity or resiliency, including the possibility that Amazon deforestation triggers broad based consequences (Steffen et al. (2018) and Flores et al. (2024)). These simulations do not account for the cascading effects discussed in Section 4. In addition, the calculations in Assunção et al. (2023b) ignore the negative effect in agriculture productivity in regions outside the Amazon in Brazil, a country that is currently the fourth largest agricultural producer and third largest exporter in the world, which are likely to result from business as usual.[27] Thus a change in trajectory from deforestation to reforestation should produce even larger gains.

Tropical rainforests are present in many other developing countries that are likely to benefit from transfer payments for reforestation. In return we would obtain more breathing time to wait for the technological solutions that would help us reach net-zero emissions.

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[27] See Araujo (2023).

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Discussion on "Carbon prices and tropical reforestation in tropical forests" at BIS Annual Conference, 28 June 2024[1]

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Introduction

This paper is motivated by the global ecological risks from Amazon deforestation. The Amazon rainforest holds over 10 percent of Earth's terrestrial biodiversity. It stores carbon equivalent of 15–20 years of global CO_2 emissions, while having a net cooling effect from evapotranspiration that helps to stabilize the Earth's climate. It also contributes up to 50 percent of rainfall in the region, and, through moisture supply, it allows biomes and economic activities to thrive in regions that would otherwise be more arid.[2]

The Amazon rainforest could soon reach a tipping point, inducing large-scale collapse and implying an irreversible loss of biodiversity. The destruction of the Amazon, therefore, may well have first order adverse implications for the Earth system.

From a policy perspective, there are two main implications. First, the ecosystem services provided by the Amazon rainforest (carbon storage, biodiversity preservation, fresh water regulation, moisture supply, etc.) make it a key public good. Second, a policy aim should be to increase the Amazon forest cover without harming biodiversity—which implies a need to reduce agricultural land and the need for appropriate governance and institutional structures to conserve or preserve the forest.[3]

Summary of the paper

The paper finds that (1) transfers of US$25 per ton of captured CO_2 would yield optimal land use with substantial reforestation; (2) optimal land use would target reforestation of areas currently used for low-productivity cattle ranching; and (3) these policies would yield CO_2 capture of 15 Gt over 30 years.

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[1] Timila Dhakhwa and William Oman (both IMF) contributed to preparing the discussion.

[2] See Flores, Bernardo M., et al. (2024), "Critical Transitions in the Amazon Forest System," *Nature* 626: 555–64.

[3] The ubiquity of non-linearities in biosphere processes suggests that biosphere protection may require quantity restrictions rather than price instruments to effectively prevent a regime shifts in ecosystems. See Dasgupta, Partha (2021), *The Economics of Biodiversity: The Dasgupta Review*, London: HM Treasury, pp. 83, 434).

The paper uses a spatial dynamic model to quantify the trade-off between cattle production and carbon capture. It exploits cross-sectional variability in cattle farming productivity and carbon absorption to estimate a shadow price of CO_2 emissions, which is used to value ecosystem services provided by preserved forest areas.

The results show that deforestation of the Amazon is an ecological and economic disaster, suggesting that carbon sequestration offers opportunities, and that “optimal” management of the Brazilian Amazon could improve outcomes substantially at a much lower cost than per previous estimates.

The contribution of this paper to the discussion on this very important topic is noteworthy and constructive. I want to add three main comments on the paper and how it could be further improved.

Additional factors should be taken into account.

The paper could take into consideration important factors that could increase the estimated impact of Amazon deforestation and reduce the effectiveness of the proposed policies, and could also include additional, broader science-based and policy considerations.

First, the analysis could distinguish between restoration of the rainforest versus reforestation through monoculture farming. Restoration is far superior to reforestation, as the latter typically consists of plantations that generate substantial biodiversity and disease risks, resulting in large costs associated with such policies.

Second, the use of industrial fertilizers and pesticides in the process of converting land into cattle ranches degrades soils and water, which creates significant pollution spillovers. These spillovers are not accounted for. The adverse impact of conversion to agricultural land may therefore be underestimated.

Third, and more conceptually, the paper could discuss the role of institutional design in driving deforestation in the Brazilian Amazon. Brazil’s legal framework is characterized by inconsistencies between civil law—which supports the titles held by landowners—and constitutional law—which supports squatters’ claims to land not in “beneficial use” (such as farming or ranching). The vagueness of the “beneficial use” criteria in Brazilian law and large uncertainty around the enforcement of the landowners’ versus the squatters’ claims to the land have been found to be a key driver of deforestation acceleration in the Brazilian Amazon.[4]

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[4] Dasgupta, Partha (2021), *The Economics of Biodiversity: The Dasgupta Review*, London: HM Treasury, p. 214.

Fourth, land tenure implications could also be discussed. In particular, the rights of Indigenous Peoples and Local Communities are emphasized in the Kunming-Montreal Global Biodiversity Framework. Tenure security of indigenous lands is critical for success in managing some of the most biodiverse areas on Earth, notably the Brazilian Amazon.[5]

The effectiveness of the recommended policies may be overstated.

The paper could take into consideration different factors that may reduce the recommended policies' effectiveness and the estimates' size. The suggested improvements to the paper could shed light on how reasonable the estimated transfers needed to substantially reduce emissions in the next three are, and could enrich the analysis by extending it to a wider scope of mechanisms at play.

First, the authors could consider for carbon sink reversals, as tree mortality can significantly reduce carbon storage. In fact, there is evidence that the south-east Brazilian Amazon is already emitting more than absorbing, and, alarmingly, that global terrestrial carbon sinks may be collapsing.[6] Reflecting uncertainty around the reliability of the carbon sink function of the Amazon forest (or parts thereof) would increase the paper's estimate of the cost of CO_2 absorption.

Second, the paper could analyze results' robustness by considering the substantial uncertainty around estimates of CO_2 absorption by tropical forests (-1.7 $GtCO_2$ ± 8.0 Gt).[7] Most importantly, the substantial variability of real-world net carbon sinks may be too large for "pay for performance" schemes to be effective.

Third, the paper could also discuss the extent to which natural cycles complement or substitute for policy measures—in other words, how to determine whether additional absorption is due to policies or natural cycles.

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[5] Dasgupta, Partha (2021), *The Economics of Biodiversity: The Dasgupta Review*, London: HM Treasury, pp. 370, 438.

[6] See Gatti, Luciana V., et al. (2021), "Amazonia as a carbon source linked to deforestation and climate change," *Nature* 595: 388–393; Ke, Piyu at al. (2024), "Low Latency Carbon Budget Analysis Reveals a Large Decline of the Land Carbon Sink in 2023," arXiv preprint:2407.12447; and Gardes-Landolfini et al. (2024), "Embedded in Nature: Nature-Related Economic and Financial Risks and Policy Considerations," *IMF Staff Climate Note* 2024/002.

[7] Harris, Nancy L., et al. (2021), "Global maps of twenty-first century forest carbon fluxes," *Nature Climate Change* 11: 234–240.

Fourth, the paper could also investigate the crucial issue of the non-permanence of stored carbon. The IPCC notes that CO_2 residence times in the atmosphere vary considerably (from a few months to over 1000 years). Residence time increases with the accumulation of carbon in the atmosphere and the gradual saturation (or, potentially, even the reversal) of carbon sinks.[8] However, Figures 2, 3, 4 and 5 implicitly assume that carbon absorption is permanent.

Fifth, the paper could take into consideration the asymmetry between CO_2 emissions and their absorption. Despite gradual saturation of sinks, CO_2 remains a key fertilizing factor for plants. This means that removing carbon from the atmosphere reduces the global forest carbon sink and that much more CO_2 than is emitted must be removed to keep same level of atmospheric CO_2 concentration, making carbon emissions and removals non-equivalent.

Policy recommendations require refinements.

My final remark is that the science-based considerations highlighted in the first two comments suggest a need for more ambitious, multilayered policies.

The science-based considerations on the dynamics of carbon sinks described in the second comment imply that ambitious policy settings are needed for schemes involving payment for carbon absorption (or reduced deforestation) to be effective.

Despite the significant challenges highlighted previously, any "payment for performance" mechanism that is introduced should be assessed based on three guiding principles: (i) public policies that impact forests (e.g., land tenure considerations, investments that affect the direct and indirect drivers of deforestation, food security policies) must be coherent; (ii) specific reforms and regulations must be case specific; and (iii) the evaluation of the effects of policy measures on both carbon absorption and biodiversity preservation must take into account theories of change and the complexity of real-world policy settings. Indeed, policy acceptability will almost always be country specific. For such large-scale policy measures, broad buy-in is necessary.[9]

In sum, while the strength of the paper is its narrow focus and quantitative results, to get policy traction there is a need to take account of the broader institutional context and the challenges posed by the key

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[8] Karsenty, Alain, “Political Economy of Forest Protection,” in Éloi Laurent and Klara Zwickl, eds. (2021), *The Routledge Handbook of the Political Economy of the Environment*, London: Routledge.

[9] On the limits of “pay for performance” schemes, see Karsenty, Alain (2021), “Les pays du Nord ne doivent pas se contenter de payer ceux du Sud pour protéger les forêts tropicales,” *Le Monde*, October 5.

science-based, biophysical characteristics of carbon sinks highlighted above. Ultimately, the complexity of the policy environment is of first-order importance to gauge whether the proposed transfers of US$25 per ton of carbon absorbed are sufficient to yield success with respect to conserving or preserving the Brazilian Amazon.

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