Challenges and opportunities to eliminate deforestation in Brazilian Amazon

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ABSTRACT

The escalating deforestation in the Amazon region poses a grave threat not only to biodiversity, but also to climate, ecosystems, and local and international communities. This paper addresses the issue of combating deforestation in the Brazilian Amazon in recent decades and proposes strategies to bring forest destruction to a halt. Although Brazil has made significant progress on this matter, there are still challenges to overcome in order to fully eradicate the practice of illegal deforestation in the region. Here, we aim to analyze the main initiatives that have been successful in reducing deforestation and identify opportunities to bring it to zero by the years 2030, 2040, and 2050. Our results suggest that actions to combat deforestation should depend on the land characteristics of the deforested areas, prioritizing the reduction in public lands, which are responsible for 51% of recent deforestation rates, followed by settlement areas and lastly by rural properties, mainly through command-and-control strategies (top-down), incentives for agroforestry reforestation and development of local bioeconomic chains.

Keywords: deforestation, Amazon, PPCDAm, budget management, public environmental management.

Introduction

Brazil presents solid knowledge in the development and implementation of anti-deforestation policies. This knowledge has emerged in response to three decades of state-sponsored deforestation in the Amazon, aligned with the public agenda of "Integrate to not Deliver". This in turn has resulted in the integration of the Amazon with other regions of the country at the cost of significant loss and degradation of natural habitats, land conflicts, and hostility towards indigenous peoples. The rapid conversion of the Brazilian Amazon's forests has also led to the emergence of forest conservation actions in the private sector and civil society groups. Many of these actions have resulted in public-private partnership initiatives and other governance mechanisms (Greenpeace 2006, 2009).

Among these policies is the creation of the Action Plan for the Prevention and Control of Deforestation in the Amazon (PPCDAm) in the early 2000s, and the revision of the Federal Forest Code (CFF) in 2012. Since its implementation in 2004, the PPCDAm has facilitated the creation of over 30 million hectares of protected areas in the Amazon, established new deforestation monitoring systems, imposed embargoes on municipalities with high deforestation rates, and contributed to the development of the Low Carbon Agriculture Program (ABC) to promote pasture restoration and integrated crop-livestock systems in the Legal Amazon (Nepstad et al., 2014a). Despite challenges in achieving high compliance rates, the revised CFF has set restrictions on the removal of native vegetation on private properties and legally established the Rural Environmental Registry (CAR), which includes over 4.6 million properties with declared boundaries available for environmental monitoring (SFB, 2022).

Private zero-deforestation policies have also emerged in the soy and meat sectors in Brazil. Soy is the primary monoculture produced in the Brazilian Amazon, and a substantial portion is exported. This necessitates that Brazilian producers not only comply with national legislation but also meet the requirements of international buyers. In 2006, when pressured by civil society, international soy processors signed the Soy Moratorium (MSoja), committing to cease purchasing soy from properties involved in deforestation. These companies formed an advisory group to assist the government and provide monitoring of soy properties. Since the implementation of the MSoja, in implementation of public anti-deforestation policies and the collapse of commodity markets in the region (Macedo et al., 2012), soy production in the Amazon is virtually free from deforestation (Gibbs et al., 2015; Kastens et al., 2017). Similarly, the meat sector signed the Cattle Agreements with Federal Prosecutors and Greenpeace in

2009, also pledging not to trade cattle from properties involved in Amazon deforestation. However, unlike the MSoja, the Cattle Agreements have had limited success in reducing deforestation, due to the complexity of the supply chain (Massoca et al., 2017) and lack of transparency in the necessary information to monitor the agreements, which could lead to leaks and cattle laundering (Gibbs et al., 2016; Alix-Garcia and Gibbs, 2017; Klingler et al., 2017).

Additionally, recently elected President Lula has committed to eliminating deforestation in the Brazilian Amazon by 2030 (Agência Brasil, 2023). In this report, we present an innovative strategy to assess the challenges and opportunities for accomplishing this commitment and achieving zero deforestation in the Brazilian Amazon by 2030. To do so, we consider the lessons learned from the implementation of the PPCDAm, which has contributed to reducing deforestation, as well as the budget allocated to the environmental agenda for the coming years. We analyzed the budget (actual and projected) of deforestation control actions implemented until 2014 to address the following questions: (i) What is the estimated budget required for deforestation control actions in different scenarios by the years 2030, 2040, and 2050? (ii) Does Brazil have sufficient financial resources to fund these deforestation control measures? (iii) What are the priority recommendations for achieving zero deforestation, considering the projected budgets? (iv) What are the main strategies that will enable the achievement of zero deforestation by 2030?

The PPCDAm and the Federal Public Budget

The PPCDAm is composed of four fundamental pillars: Territorial and Land Planning, Environmental Monitoring and Control, Promotion of Sustainable Activities, and Normative and Economic Instruments. Its implementation was carried out through an integrated strategy involving various ministries and federal agencies, and the budget came from diverse sources. As a result, estimating the budget figures is challenging. Verdum (2017) conducted the herculean task of estimating federal expenditures for combating deforestation, and the results were impressive. The total budget (projected) for the first three pillars of action amounted to R$ 13.8 billion for the 2007- 2014 period. However, the actual budget utilization reached R$ 8.2 billion (Figure 1), resulting in a budget inefficiency of approximately 41%.

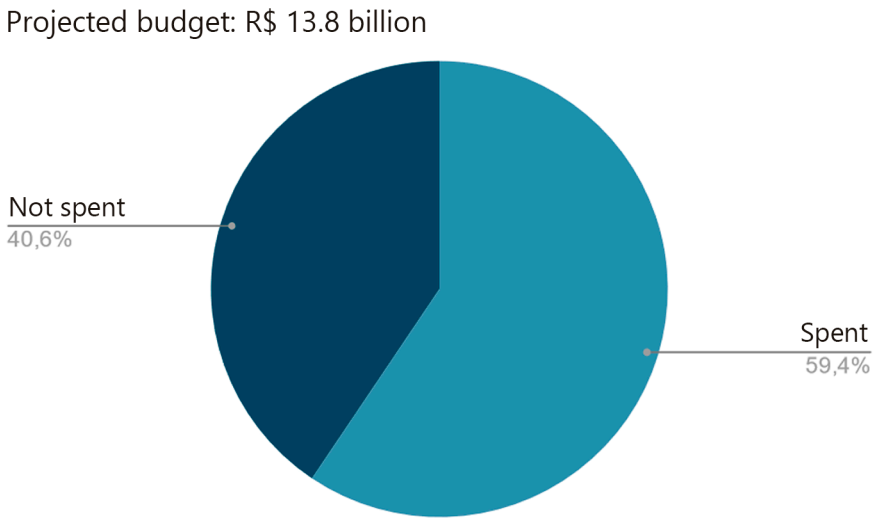

Figure 1 Projected vs. Spent Budget (R$ billion). *Source:* Adapted from Verdum (2017).

Out of the total budget, R$ 1.25 billion was allocated for the Territorial and Land Planning between 2007 and 2014. As for the Environmental Monitoring and Control pillar, the budget expenditure was R$ 1.66 billion. The remaining R$ 5.22 billion corresponded to the Promotion of Sustainable Activities pillar budget (Table 1).

Table 1 The PPCDAm and the Federal Public Budget (R$ million).

Planning Axis (2007-2014)			Monitoring Axis (2007-2014)			Promotion Axis (2007-2014)		
Year	Projected (R$ millions)	Spent (R$ millions)	Year	Projected (R$ millions)	Spent (R$ millions)	Year	Projected (R$ millions)	Spent (R$ millions)
2007	221,6	163,8	2007	142,8	108,4	2007	1.440,5	1.315,5
2008	316,2	172,6	2008	261,2	223,2	2008	2.387,3	1.914,9
2009	374,1	178,7	2009	425,9	333,8	2009	970,1	708,2
2010	539,4	304,7	2010	348,2	293,1	2010	1.189,4	645,9
2011	391,8	229,8	2011	262,5	225,4	2011	617,1	468,4
2012	115,5	7,1	2012	248,8	158,9	2012	343,8	63,3
2013	299,7	42,3	2013	205,3	145,5	2013	1.055,1	88,9
2014	545,9	156,8	2014	247,4	173	2014	902,6	17,2

Source: Adapted from Verdum (2017).

In summary, according to Verdum's survey in 2017, the PPCDAm's total realized budget amounted to approximately R$ 8.2 billion (Figure 2), with 78%

of the funds expended during the Lula administration (2007-2010) and 22% during the Dilma administration (2011-2014). The majority of this investment, up to 88%, occurred during the Lula era (around R$ 819.8 million between 2007-2010), and it began to decline during the Dilma era (2011-2014).

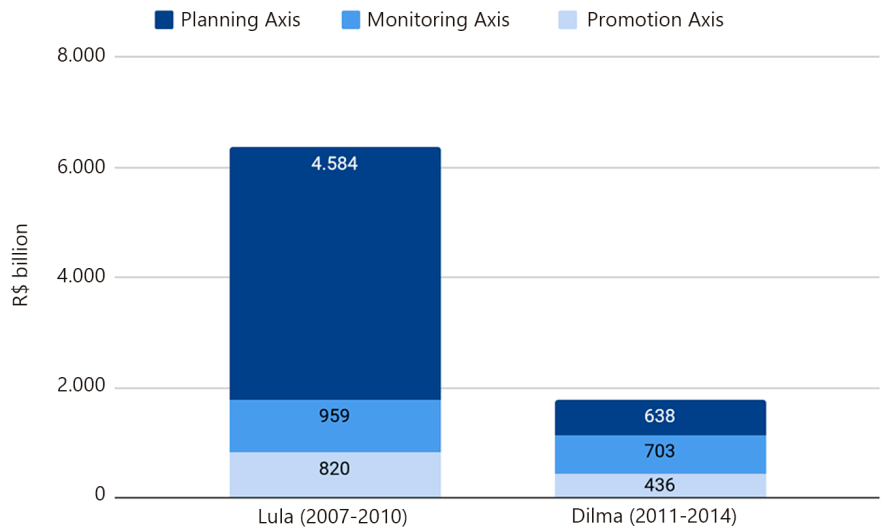

Figure 2 PPCDAm budget in the governments of Lula and Dilma. *Source:* Adapted from Verdum (2017).

Budget Scenario Forecast for 2030, 2040, and 2050

The implementation of the PPCDAm was divided into four distinct phases, highlighted in different colors in Figure 3. The first phase spanned the years between 2005 and 2008 (dark green), followed by the second phase from 2009 to 2011 (light green), the third phase from 2012 to 2015 (light blue), and the final phase from 2016 to 2020 (orange). According to PRODES (Program for Monitoring the Deforestation of the Brazilian Amazon Forest by Satellite), the largest annual decline in deforestation occurred during the first two phases, from 2005 to 2012, with an average annual reduction of 19%. Hence, this period was considered the calibration period for this study. Given the lack of information on the budget utilization in 2005 and 2006, we estimated the costs for deforestation reduction using the budgetary information available between 2007 and 2014.

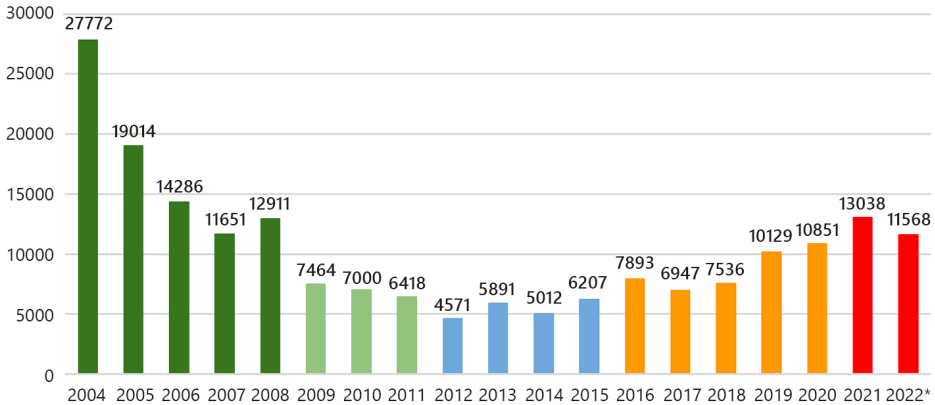

Figure 3 Deforestation in km² between 2004 and 2022). *Source*: INPE (2022).[1].

We propose a deforestation reduction model summarized in Table 2 based on the following assumptions: 1) For the period 2023-2030, an average annual reduction rate of 19% was proposed, similar to the 2005-2012 calibration period – which, as previously mentioned, had the highest observed reduction in deforestation rates; 2) Between 2031 and 2040, an average annual deforestation reduction rate of 9% was proposed, which represents approximately half of the calibration period rate; 3) For the final period, between 2041 and 2050, the model considered an average rate of 5% per year, corresponding once again to approximately half of the previous period rate.

Table 2 Deforestation reduction model in different scenarios (2030, 2040, and 2050).

Scenarios	Period	Annual Deforestation Reduction Rate (%)
Calibration	2005-2012	– 19%
A (Historical reduction)	2023-2030	– 19%
B (~ 50% of A)	2031-2040	– 9%
C (~ 50% of B)	2041-2050	– 5%

Source: Own elaboration.

1. The PRODES-Amazon released deforestation data up to 11/30/2022. Therefore, the data for December 2022 is not included in the information above.

The actual budget utilized to reduce deforestation from 11,651 km² in 2007 to 5,012 km² in 2014, totalizing approximately 6.6 million km², amounted to R$ 8.2 billion. This corresponded to public investment of around R$ 1.23 million per km² per year, and hence, was considered a benchmark in this study (Figure 4).

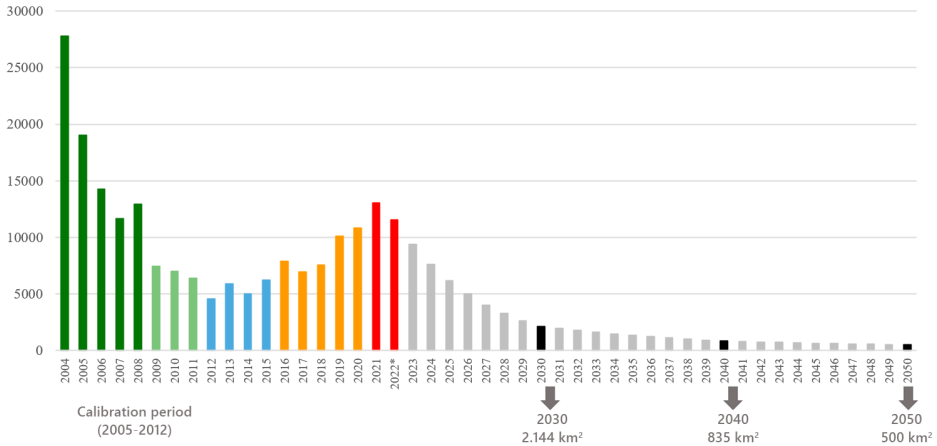

Figure 4 Deforestation reduction in 2030, 2040 and 2050. *Source:* Own elaboration based on INPE (2022).

According to the model presented in Table 1, the scenario for deforestation reduction between 2023 and 2030 predicts an average annual reduction rate of 19%, resulting in a decrease in deforestation from 11,568 km² at the end of 2022 to 2,144 km² by 2030, totalizing a reduction of 9,424 km². The estimated budget required to achieve this goal is approximately R$ 11.63 billion.[2] It is important to note that the original deforestation reduction rate of 19% was achieved during a period when the governance of the PPCDAm was primarily led by the Office of the Chief of Staff. During this period, ministerial integration efforts were coordinated directly by the government agency linked to the presidency of the republic (the head of the executive branch), providing significant institutional strength for implementing operational plans. Therefore, based on this study, it is assumed that the current governance against deforestation considers the relevance of this framework, at least until 2030.

Regarding the scenario between 2031 and 2040, where the average annual deforestation reduction rate is estimated at 9%, deforestation is reduced from 1,951 km² in 2031 to 835 km² by 2040, totalizing 1,116 km². The additional

2. The budgets (2023-2030; 2031-2040 and 2041-2050) have been estimated in nominal values. For more details, see the "Study limitations" section.

budget required to achieve this target is estimated at approximately R$ 1.32 billion. Finally, the scenario between 2041 and 2050 predicts an average annual reduction rate of 5% in deforestation, resulting in reducing deforestation from 793 km² to 500 km², totalizing 293 km². The estimated additional cost to achieve this goal is R$ 0.36 billion.

Table 3 Deforestation between 2004 and 2022 and estimation for 2030, 2040 and 2050.

Year	Deforestation (km²)	Year	Deforestation (km²)	Year	Deforestation (km²)
2004	27772	2020	10851	2036	1217
2005	19014	2021	13038	2037	1108
2006	14286	2022*	11568	2038	1008
2007	11651	2023	9370	2039	917
2008	12911	2024	7590	**2040**	**835**
2009	7464	2025	6148	2041	793
2010	7000	2026	4980	2042	753
2011	6418	2027	4034	2043	716
2012	4571	2028	3267	2044	680
2013	5891	2029	2646	2045	646
2014	5012	**2030**	**2144**	2046	614
2015	6207	2031	1951	2047	583
2016	7893	2032	1775	2048	554
2017	6947	2033	1615	2049	526
2018	7536	2034	1470	**2050**	**500**
2019	10129	2035	1338		

Source: Until 2022, information was extracted from INPE (2022). From 2023 onwards, the elaboration was its own.

In summary, the total estimated cost for implementing the deforestation reduction policy, according to the proposed model, amounts to R$ 13.28 billion. However, considering the same inefficiency rate shown in Figure 1, of approximately 41%, the projected (budgeted) amount should exceed R$ 21 billion by 2050.

The discussion surrounding the availability of financial resources for the endeavor of deforestation reduction is a pertinent issue. The projected budget for the Ministry of Environment and Climate Change (MMAMC) in 2023 amounts to approximately R$ 3 billion, as indicated in the 2023 Budget Bill. Additionally, only a portion of this amount, approximately R$ 340 million, is allocated to the Program for Deforestation and Fire Prevention and Control in Biomes. However, additional financial sources can be directed towards environmental initiatives through federal government secretariats and subsecretariats, such as the Secre-

tariat of Green Economy, Decarbonization, and Bioindustry, linked to the Ministry of Development, Industry, Trade, and Services, as well as the subsecretariats of Sustainable Economic Development and Sustainable Development Financing, both linked to the Ministry of Finance.

Table 4 Estimated cost (R$ billion).

Period	Estimated cost (R$ billion)	Budget type
2023-2030	11,63	Spent
2023-2030	18,55	Projected
2031-2040	1,32	Spent
2031-2040	2,19	Projected
2041-2050	0,36	Spent
2041-2050	0,57	Projected
Total cost	13,28	Spent
Total cost	21,17	Projected

An additional source of funding to combat deforestation in the Amazon is the immediate cancellation of the amnesty for environmental fines granted during the Bolsonaro government (2018-2022), which amounted to approximately R$ 18 billion, and the reinstatement of the fine and taxation system by environmental authorities. Additionally, plans to resume the foreign resources from the Amazon Fund would imply an estimate of at least R$ 3.6 billion for allocation to new projects (Bastos, 2023).

Strategies tied to potential actions in time and space to achieve zero deforestation in the Legal Amazon by 2030

While understanding and quantifying available financial resources is an important process for the operationalization of a public policy, it is necessary to incorporate different strategies to achieve the goal of Zero Deforestation in the Amazon. This involves prioritizing actions, maintaining or implementing well-established surveillance measures, and suggesting innovative mechanisms to combat deforestation. Here, we build upon the existing theoretical-economic model by proposing a second theoretical model based on the axes Deforestation Rate → Time (Figure 5). The 'complexity' (z-axis) in the theoretical model is considered a subjective vector, meaning that the difficult measurement of 'complexity' prevents us from stating that one priority action is 'more' or 'less' complex than another. However, we emphasize the importance of considering

the 'complexity' as the proposed actions involve multiple factors for their effective implementation.

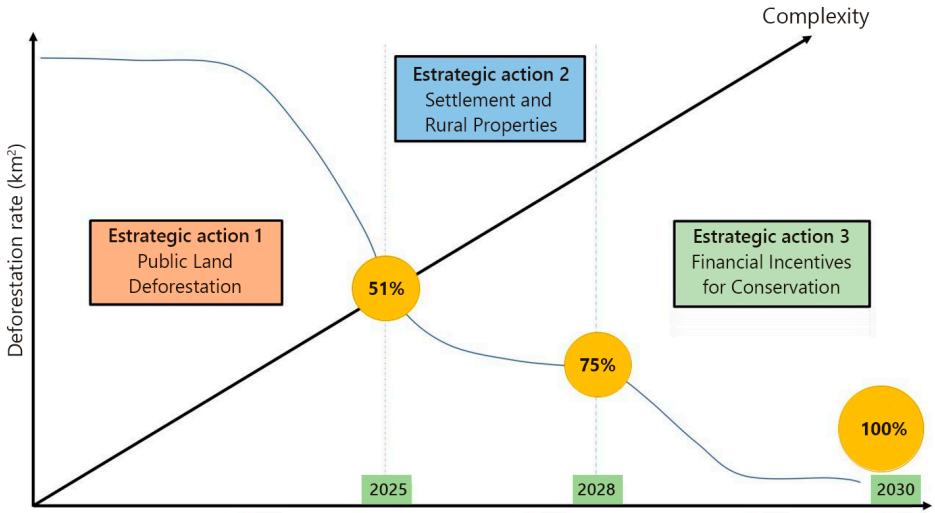

Figure 5 Representation of the theoretical model for achieving zero deforestation by 2030. The aim is to significantly reduce deforestation by 2030, employing different, non-conflicting, and complementary strategies from the present (2025) to 2030. Three distinct strategies have been defined to address the main drivers of deforestation in the Amazon (Strategies 1 and 2), leading to Strategy 3 (long-term | 2028-2030), which focuses on conservation incentives. These strategic actions are not mutually exclusive, which means that a specific action can (and should) be implemented simultaneously with another. For example, financial incentives are crucial for actions targeting the end of deforestation in Undesignated Public Lands (Strategic Action 1). Conversely, in the long-term perspective (2028-2030), strengthening the bioeconomy and nature-based solutions will be prioritized to enhance the biome's resilience against historical degradation drivers, such as deforestation.

The proposal, therefore, stems from identifying priority mechanisms to combat deforestation, such as identifying Conservation Units and Indigenous Territories that concentrate the highest deforestation rates, as well as focusing on Undesignated Public Lands (2023-2025) (Prioli et al., 2023; Qin et al., 2023; Moutinho & Azevedo-Ramos, 2023). It extends to the regularization and enforcement of the Rural Environmental Registry - CAR (2025-2028) (Azevedo-Ramos et al., 2020; Stabile et al., 2022; Bergamo et al., 2022), and includes complementary strategies that enable the achievement of the zero-deforestation goal, along with strategies to mitigate legal deforestation (Stabile et al., 2022). It also encompasses proposals for forest restoration (Gastauer et al., 2020), utilization of international funds, bioeconomy, nature-based solutions, and long-term pu-

blic policies (Bergamo et al., 2022; Moutinho et al., 2016; Moutinho & Azevedo-Ramos, 2023).

Actions to combat deforestation

Strategic Action 1 – Deforestation in public lands

Brazil has approximately 56 million hectares (Mha) of Public Forests, areas designated for conservation and/or sustainable resource use, with nearly 92% concentrated in the Amazon region (National Registry of Public Forests, 2020). However, around 21% of the total Brazilian Public Forests remain undesignated. These areas lack regulation and can become targets for improper/irregular/illegal appropriation. Once again, it is in the Amazon region where the vast majority of undesignated Public Forests are found, accounting for about 50 Mha (Moutinho & Azevedo-Ramos, 2023).

The failure to designate these forest areas creates opportunities for land grabbing. According to the Rural Environmental Registry (CAR), which is self-declaratory, nearly 12 Mha (23% of the 50 Mha) of undesignated Public Forests in the Legal Amazon were irregularly registered as rural properties in the National System of Rural Environmental Registry (Azevedo-Ramos et al., 2020). Out of this total, around 8 Mha are in state-owned Public Forests, and 3.5 Mha are in federal Public Forests. A direct consequence of irregular self-declaration through the CAR is deforestation and the potential degradation of well-preserved areas (approximately 66% of the irregularly declared areas have been deforested). Moreover, there is a legal pretext that prohibits the occupation of rural properties located in federal public lands (i.e., land titling) without a specific purpose determined by the government (Law 11.952/2009). However, non-compliance with the law finds legal support due to Decree No. 10.952/2020. The decree assumes that any public forest can be designated for land regularization when the responsible entities for these areas do not explicitly manifest an interest in their designation (Brito, 2023).

Consequently, the first strategic action should involve combating the improper appropriation of self-declared state-owned Public Forests. This action would require command-and-control over erroneously self-declared areas, imposing legal and financial penalties, preventing and revoking requests for land regularization that overlap with Public Forests, and enforcing severe penalties for irregular entries through the Rural Environmental Registry. The amendment of Decree No. 10.592/2020 is also necessary. The second strategy focuses on

direct intervention in the states with the highest deforestation rates in undesignated Public Forests in the Legal Amazon: Pará (56.5%), Rondônia (18.75%), and Amazonas (14.1%). By restricting illegal practices in these states, a greater reduction in deforestation can be expected as a whole.

The third strategy, finally, involves urgently allocating these undesignated territories to Conservation Units, Homologated Indigenous Territories, and/or Areas of Sustainable Use. Brito (2023) suggests that such undesignated federal Public Forests should be promptly converted into Areas of Provisional Administrative Limitation, which would then expedite their designation as Conservation Units. As indicated by the proposed economic model (Table 4), this strategy is estimated to cost at least R$ 3.5 billion, allocated between the years 2023 and 2025.

Deforestation in Protected Areas: The Importance of Indigenous Territories and Conservation Units in the Legal Amazon

The challenge of preserving and conserving forested areas in Brazil is immense. The Legal Amazon region covers more than 5.2 million km^2, with 83% of its area covered by forests (Prioli et al., 2023). Over half of the territory (52%) in the Legal Amazon is under some form of protected status, with 22% of the region being Indigenous Lands (ILs) and 30% consisting of Conservation Units (CUs) (Qin et al., 2023; Prioli et al., 2023). Among the CUs, 37% are designated as Strict Protection, while 63% are classified as Sustainable Use (Pacheco et al., 2018).

When properly implemented and managed, CUs and ILs act as shields against deforestation. Indeed, Qin et al. (2019) indicated that deforestation rates within Protected Areas (ILs and CUs) are 10 times lower than in unprotected areas. In terms of deforestation within CUs, it accounted for an average of 7.2% of the total deforestation in the Legal Amazon from 2008 to 2022 (Terra Brasilis/INPE, 2023).

Only three CUs (out of a total of 4,200) accounted for 71% of the deforestation that occurred in these areas between 2008 and 2022: (i) Triunfo do Xingu Environmental Protection Area (APA) (46%); (ii) Jamanxim National Forest (FLONA) (13%); and (iii) Jaci-Paraná Extractive Reserve (RESEX) (12%). In addition, in 2022, the Tapajós APA also stood out with 10% of the deforestation within Amazonian CUs (Terra Brasilis/INPE, 2023). It is worth noting that these four CUs are located in priority municipalities in terms of prevention, monitoring, and control of deforestation in the Amazon (MMA Ordinances 028/2008 and 361/2017) and were created during the first phase of the PPCDAm as a strategy to prevent deforestation (Table 5).

Table 5 Protected Areas with deforestation rates exceeding 10% within Legal Amazon Conservation Units during the period from 2008 to 2022.

Conservation units	Places (municipalities)	Establishment´s year	The managing organization	Management plan
Triunfo do Xingu environmental Protection area	Altamira (PA) and São Félix do Xingu (PA)	2006	Instituto de Desenvolvimento Florestal e da Biodiversidade do Estado do Pará (Ideflor-bio-PA)	There is no management plan available. The management council was established in 2011.
Jamanxim National Forest	Itaituba (PA) and Novo Progresso (PA)	2006	Unidade Especial Avançada do ICMBio de Itaituba – PA	The management plan was developed in 2010 and the management council was established in 2011.
Jaci-Paraná Extractive Reserve	Porto Velho (RO), Campo Novo de Rondônia (RO) and Nova Mamoré (RO)	1996	Coordenadoria de Unidades de Conservação CUC/SEDAM-RO	There is no management plan available. The management council was established in 2001.
Triunfo do Xingu environmental Protection area	Altamira (PA) and São Félix do Xingu (PA)	2006	Unidade Especial Avançada do ICMBio de Itaituba – PA	There is no management plan available. The management council was established in 2011.

Source: Elaborated by the authors. Note: The underlined municipalities are included in the list of priority municipalities for deforestation prevention, monitoring, and control actions (MMA Ordinances 028/2008 and 361/2017).

To develop effective strategies to combat illegal activities in CUs, we recommend the following:

- Development or updating of management plans for CUs, establishment (and strengthening) of management councils, and implementation of their respective management plans (projects that ensure the conservation objective).
- Assessment of the conservation impact and use of natural resources in Amazonian CUs.
- Land regularization of CUs, creation of new areas, and implementation of command-and-control mechanisms to cease illegal activities such as deforestation, hunting, illegal fishing, and mining.
- Ecological restoration of degraded areas.

- Strengthening the sense of belonging and contribution to social well-being in CUs. Involvement of local communities in CUs management, promotion of technical support and social capacity building for community management.
- Contribution to the establishment of sustainable and equitable bioeconomic models, with monitoring of the socioeconomic condition of Amazonians at the local level regarding employment opportunities, fair remuneration, and labor quality.
- Guaranteeing benefit-sharing according to the National Policy on Access and Benefit Sharing of Socio-biodiversity.

Preservation of Indigenous Lands (ILs), along with CUs, is crucial for the integrity of the forest (Sze et al., 2022), conservation of carbon stocks (Nogueira et al., 2018; Saatchi et al., 2011; Walker et al., 2014), maintenance of biodiversity (Fernández-Llamazares et al., 2021), climate regulation (Silvério et al., 2015; Baker & Spracklen, 2019), and preservation of the cultural diversity of indigenous peoples (Cunha & Almeida, 2000). Indigenous Territories in the Legal Amazon are part of the Public Lands system, with low absolute deforestation rates (3%) when compared to the accumulated deforestation in non-designated Public Lands. Approximately 58% of the Brazilian Legal Amazon is occupied by 352,000 indigenous peoples from 427 ILs, covering an area of 115,294,899 ha (Instituto Socioambiental, 2023). However, since 2013, deforestation in ILs has increased by 129%, with the highest deforestation (195%) occurring between 2019 and 2021 (Silva-Junior et al., 2023). Among all ILs in the Brazilian Legal Amazon, the Ituna/Itatá and Piripkura ILs experienced the highest illegal deforestation from 2019 to 2021 (Fellows et al., 2023). This scenario is primarily driven by illegal mining, which has increased from 1% in 2016 to 19% by mid-2022 (Silva-Junior et al., 2023). The political discourse during the Bolsonaro period (2019-2022) and the potential legalization of commercial mining in ILs (PL 191/2020), along with the increase in gold prices, may be behind this alarming situation (Siqueira-Gay et al., 2020).

Several studies have indicated that this 191/2020 bill could impact over 20% of the forest, resulting in a loss of at least US$5 billion per year due to the benefits provided by forest (Siqueira-Gay et al., 2020), leading to severe consequences for indigenous peoples, especially isolated groups at risk (Villén-Pérez et al., 2022). The bill would also have a negative impact on ecosystems (such as forest fragmentation, microclimate changes, biodiversity loss, trophic magnification, contamination of groundwater and water bodies, and carbon stock

reduction), due to the creation of roads and urban centers generated by mining activities (Siqueira-Gay et al., 2020, 2022; Fellows et al., 2023).

According to Rorato et al. (2022), the most vulnerable ILs in the entire Brazilian Legal Amazon are located precisely in the Arc of Deforestation region, specifically in the Arc's southern part, as well as in Roraima and Pará (Rorato et al., 2022). The five most vulnerable ILs are (i) Tuwa Apekuokawera (PA); (ii) Praia do Índio (PA); (iii) Lagoa Comprida (MA); (iv) Urucu/Juruá (MA); (v) Rio Pindaré (MA). Dos Santos et al. (2022) identified the five ILs with the highest cumulative deforestation rates (from 1988 to 2021): (i) Alto Rio Negro (AM); (ii) Andirá-Marau (AM/PA); (iii) Cachoeira Seca (PA); (iv) Apyterewa (PA); (v) Alto Turiaçú (MA).

Other factors contributing to higher deforestation rates in ILs are forest fires and land grabbing. The former is mainly associated with mining activities and land grabbing on public lands (Fellows et al., 2021). Apyterewa and Kayapó (isolated groups) were the ILs with the most forest fires between 2018 and 2021, with a 50% increase in forest fires in Apyterewa IL in three years (Fellows et al., 2023). Land grabbing occurs through the self-declaration overlap strategy via the Rural Environmental Registry (CAR). In this case, landowners do not overlap in non-designated Public Lands but maintain this illegal strategy in Indigenous Territories. For example, the Ituna/Itatá and Tenharim do Igarapé Preto ILs had 94% of their territorial area overlapping with CAR, while the Piritti and Pirikura ILs had 56% and 22% overlap during 2018-2021 (Fellows et al., 2023). In 2019, the territory overlapping with CAR resulted in a 41% deforestation rate in ILs (Fellows et al., 2021).

Theoretically, ILs are protected by law. However, the lack of registration and territorial demarcation of ILs, along with the overlapping of Conservation Units and CARs, and the invasion by miners and land grabbers, make ILs vulnerable territories (Fellows et al., 2023). Therefore, to create strategies to combat illegal activities in ILs, we recommend:

- Strengthening Indigenous Land Rights (Article 231) and suspending any regulations that undermine the rights of Indigenous peoples (PL 191/2020).
- Registration of Indigenous Lands (ILs) and cancellation of all Rural Environmental Registrations (CARs) within ILs.
- Implementing rigorous command-and-control policies in ILs, removing illegal miners and land grabbers, and imposing substantial penalties for those who violate the law.

- Empowering the representative power of FUNAI, IBAMA, Federal Police, and the Federal Public Ministry.
- Developing social, biotechnological, and ecological projects that demonstrate the crucial role of indigenous peoples in preserving the integrity of the Amazon Rainforest, climate, biodiversity, and the bioeconomy of Amazonian natural products.
- Establishing sustainable projects that address not only contaminated water but also include the practice and education of bioremediation for polluted soils and plants.
- Creating an Emergency Rescue Program for isolated indigenous peoples residing in high-risk areas, with the support of the Federal Police and FUNAI, particularly through brigades.
- Assigning annual investments of approximately R$1 billion for the maintenance, establishment, and allocation of Indigenous Territories and Conservation Units.

Achieving zero deforestation in Protected Areas and ILs begins with identifying key areas with the highest deforestation and vulnerability rates and consistently investing and allocating resources, amounting to R$1 billion annually between 2023 and 2025 (Table 4). Unlike Undesignated Public Lands, which account for 30% of all deforestation in the Legal Amazon, the complexity and timeline to achieve zero deforestation in these protected areas should be lower, yielding positive results in a shorter timeframe. A combination of top-down strategies, such as command-and-control, rigorous enforcement, an end to environmental fine forgiveness, maintenance, establishment, demarcation, regularization, and implementation of Protected Areas/Indigenous Lands, along with bottom-up strategies, including support for socio-economic alternatives in ILs and Protected Areas, particularly Sustainable Use Conservation Units and Extractive Reserves (Pacheco et al., 2018), and strengthening collaborative management by traditional communities (Freitas et al., 2020), can enable the ambitious reduction of up to 51% of deforestation by 2030.

Strategic Action 2 – Settlements and Rural Properties

A significant portion of illegal deforestation in the Amazon Rainforest is linked to the production chain of beef and soy in rural settlements and private properties. In rural settlements, although these supply chains account for 20% of the total deforestation, over 50% occurs in only 10 settlements (Alencar et al., 2016). Moreover, among the deforested areas in rural properties registered in

the Rural Environmental Registry (CAR) by 2020, 45% did not comply with the Forest Code legislation due to inadequate preservation of Permanent Protection Areas (APPs) and Legal Reserves, largely driven by illegal deforestation for pastureland (Rajão et al., 2020). Researchers estimate that around 48% of all beef and 22% of all soy exported to the European Union (EU) are linked to illegal deforestation in the Amazon, despite the soy moratorium agreement. In addition to incomplete property registration in CAR, especially regarding illegally seized lands, difficulties in the traceability of export products pose serious risks to monitoring the international trade chains of Amazonian products (Rajão et al., 2020). This suggests that control and monitoring mechanisms for the origin of export products are insufficient to identify and combat production chains associated with deforested areas.

These data impose serious risks to commodity exports to the EU, considering the potential advancement in the Mercosur-EU agreement sought by the third term of the Lula government. The current government has shown commitment to curbing deforestation and combating environmental crimes, receiving support from countries such as Germany, France, Norway, and likely the United States, as financiers of the Amazon Fund, to strengthen Brazil's commitment to international agreements. An initial measure by the new Minister of the Environment, Marina Silva, was to restore and restructure the PPCDAm, a successful program in reducing deforestation in the past (Sousa-Junior et al., 2021) but deemed insufficient in this new post-Bolsonaro scenario to achieve President Lula's electoral promise of zero deforestation in the Amazon by 2030 due to additional carbon emissions linked to increased droughts and wildfires (Aragão et al., 2018).

Given this new scenario, our proposal to combat illegal deforestation in private properties and rural settlements focuses on medium-term measures (from 2025 to 2028) for allocating resources dedicated to complementary actions to the PPCDAm. Therefore, we recommend the following:

- Law enforcement and punishment for offenders.
- Remediate environmental damages caused.
- Increase transparency in the supply chain and hold corporations accountable for using products linked to illegal deforestation.
- Strengthen the PPCDAm and CAR in private properties and rural settlements, while providing financial incentives to landowners who comply with Forest Code legislation, in conjunction with restricting access to credit for those who fail to comply with the PRAD (Recovery Plan for Degraded Areas).

- Enhance and expand the capacity of international markets to monitor the origin of commodities produced in the Amazon and broaden mechanisms for product embargoes resulting from deforestation (Golnow et al., 2018; Alix-Garcia & Gibbs, 2017).
- Allocate a portion of the Amazon Fund resources to implement technologies for identifying the origin of exported beef and soy through genetic monitoring.
- Invest at least R$3.5 billion from 2023 to 2028, particularly to achieve the projected reduction target of up to 75% of deforestation (Figure 5).

Strategic Action 3 – Financial Incentives for Conservation

The economic development model in the Amazon has so far been based on resource extraction and exploitation, which has historically resulted in socio-economic and environmental problems. In summary, the future bioeconomy strategy for Amazon should go beyond its forest products/resources. However, as indicated by our theoretical model (Figures 5 and 6), reconciling the advancement of the bioeconomy with zero deforestation in the Amazon will be of very high complexity.

The Amazon represents a vast territory with a low density of educational institutions, research facilities, and technological centers for the improvement of existing production chains. This technical assistance bottleneck, however, can be utilized to create new jobs and attract qualified personnel to the region, fostering the establishment of companies and government institutions. Initiatives such as the Amazon Institute of Technology (AmIT) seem to present a promising path in this regard. Achieving zero net deforestation in Private Protection Areas (APPs) and Legal Reserves in private properties and settlements will depend on strengthening command-and-control strategies, territorial planning, and land regularization, as seen in the first three phases of the PPCDAm. Simultaneously, investments are needed in the exploration of biotechnological derivatives from the immense biodiversity of the Amazon, financing for the bioeconomic transition, sustainable intensification of agriculture, promotion of low-carbon agriculture, agroforestry systems, including the possibility of reforestation with economically valuable species, and other nature-based solutions.

In this stage (2028-2030), the focus of strategic actions will be on advancing the transition to a bioeconomy, which will be facilitated by a net reduction in deforestation of up to 70% compared to the current projection for 2023. With the drastic reduction in deforestation, it is imperative to base the bioeconomy

strategy on the sustainable exploitation of non-timber forest resources, such as açaí, Brazil nuts, and andiroba, as well as sustainable management of pirarucu fish (Freitas et al., 2020). The bioeconomy of the Amazon should incorporate its key stakeholders in the use and management of these resources: traditional communities, such as riverine dwellers and/or chestnut gatherers, as well as indigenous peoples. According to Nobre et al. (2021), Amazonian citizenship can be a key element for the development of the Amazonian bioeconomy, combining traditional knowledge and scientific research. Although we consider this stage as the final one among the strategic actions (Figure 5), we acknowledge that the bioeconomy must be strengthened through public policies, cultural diversity, and product diversification, particularly non-timber products, and that investments must be continuous. The path to achieving zero residual deforestation from 2030 onwards, therefore, requires investments of approximately R$10 billion. This amount should be seen as a cost of opportunity compared to the numerous projected impacts if deforestation reaches a point of no return (Nobre et al., 2016), especially if the 40% threshold of the total Amazon area for deforestation is breached.

Finally, we strongly advocate for the implementation of a highly intricate final stage, as it is crucial to understand and embrace the significance of financial incentives within the Amazon region, particularly through the lens of the bioeconomy. This endeavor requires the robust fortification of public policies, active engagement of the diverse Amazonian cultural heritage, non-timber product diversification, and that the public policy framework equally favors the different actors in this policy/strategy towards zero deforestation.

Final remarks

Despite the enormous challenges in achieving zero deforestation by 2030, the proposed model (Figures 5 and 6) presents an unprecedent approach by combining projected and actual government budgets aligned with top-down and bottom-up strategies. The three different strategies were designed with the aim of providing guidance and suggestions for public agents to promptly identify the main drivers of deforestation and public policies to be fought and/or implemented to achieve the proposed goals for 2025, 2028 and 2030. It is worth noting, however, that these strategies are not mutually exclusive. Under an effective governance/policy proposal, it is possible (and even recommended) for them to be implemented concurrently.

To fully realize the effectiveness of the proposed models (i.e., economic-theoretical model), various government challenges need to be addressed, such as changes in environmental and social legislation, land demarcation, and the adoption of rigorous measures against illegal actions. In addition to these measures, new complementary strategies, such as increased financial incentives for the conservation of the Legal Amazon, massive ecological restoration and mapping for the suspension of credit in the national financial system for owners involved in environmental and social illegalities, for example, should be implemented. By highlighting the increasing complexity of decision-making with multiple strategies over time, the model presented in this study serves as an analytical tool, capable of contributing to concrete actions at different scales, urgencies, and intervention intensities to achieve the ambitious goal of zero deforestation by 2030.

Study limitations

The first limitation of this study pertains to its development. This essay was the result of a theoretical-practical exercise proposed at the São Paulo School of Advanced Science (ESPCA) during two weeks between November and December 2022. The authors do not aim to propose a state-of-the-art model on the subject, but rather to present arguments and proposals for the debate to be expanded and discussed in various sectors of Brazilian society.

In addition, it is important to note the attempt to estimate the financial costs of deforestation reduction. Besides the already demonstrated difficulty in gathering the costs incurred in the PPCDam between 2005 and 2022, estimating the future value until 2050 is also problematic. To perform a valuation of the future, that is, to estimate the Net Present Value (NPV), mainstream economics advocates for the use of an Intertemporal Discount Rate as a cost-benefit analysis tool. Researchers in Ecological Economics, who question the environmental perspective of conventional economists, debate whether a higher or lower discount rate could favor the environment (Daly & Farley 2016). In terms of evaluating future projects, a high discount rate favors projects with costs primarily in the future and profits in the present, while penalizing those with current costs and future profits, as is the case with the present deforestation reduction model.

To avoid discussing whether the discount rate was underestimated or overestimated, the authors of this study chose to estimate the costs in nominal values, that is, without using a pre-established intertemporal discount rate.

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Ethics – This study does not involve human subjects and/or clinical trials that should be approved by the Institutional Ethics Committee.

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