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How to halt deforestation in the Amazon? A Bayesian process-tracing approach

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ABSTRACT

In this paper, we employ for the first time a Bayesian process-tracing approach to assess the role of different interventions designed to halt deforestation. We applied the methodology to six initiatives implemented between 2006 and 2019 in the municipality of São Felix do Xingu, namely: (i) institution of protected areas, (ii) environmental monitoring and enforcement, (iii) credit restrictions, (iv) commodity agreements, (v) multi-stakeholder processes, and (vi) value chain projects. Bayesian process tracing is an alternative to traditional counterfactual approaches that allows the gleaning of in-depth insights into 'causal chain' mechanisms and complex interrelationships in individual cases, rather than identifying common or cross-cutting features across different cases. Contrary to traditional process-tracing methodologies, the Bayesian approach provides analytical transparency and replicability through a formal and fine-grained assessment of the strength of the evidence. We assessed 31 individual pieces of evidence, developed using data collected through a variety of quantitative and qualitative methods. We grouped these into interventions spanning three periods of time and traced the causal mechanisms linked to their success or failure. In total, we developed nine theory components. Our results reveal that we are practically certain that four theory components are true. We are also reasonably certain or highly confident that four other theory components are true, and only cautiously confident that one component is true. Drawing on the nine components, we offer a composite theory explaining deforestation outcomes. Our findings provide four implications for global debates. Namely, they provide a strong case for the importance of conceptually distinguishing: the types of actors targeted (e.g., smallholder or medium-to-large landholders) and the frontier status (i.e., whether interventions take place in active frontiers or in consolidated areas). They also prove that interventions may be well implemented for a certain period but can lose effectiveness over time. Finally, our findings call attention to synergies among interventions, and in particular to the combination of regulatory interventions to halt frontier expansion with market-based approaches to incentivize non-deforestation behaviour.

1. Introduction

Determining the causal effects and causal mechanisms of interventions designed to reduce tropical deforestation has been a major concern in global debates (Busch and Ferretti-Gallon, 2017; Soares-Filho and Rajão, 2018). The emergence of new types of interventions beyond the remit of typical public regulation has rendered the regulatory environment around land-use decision-making increasingly complex, further complicating the assessment of interventions' effectiveness (Lemos and Agrawal, 2006). This is particularly important, since halting deforestation of tropical forests (and recovering degraded forests) can contribute up to 30% of the total mitigation needed between now and 2030 to limit warming to below 2 °C (Seymour and Busch, 2016).

In recent years, a mounting body of work has offered meaningful contributions to advance our understanding of what can halt tropical deforestation. The use of counterfactual studies, particularly using

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quasi-experimental evaluation methods, has largely contributed to this trend (Baylis et al., 2016). By comparing a case in which intervention X is observed (the 'treatment' variable) with a similar situation in which the intervention is not observed (the counterfactual), researchers are able to provide a precise estimate of the contribution of a specific intervention to a particular outcome (Meyfroidt, 2015). These studies often use empirical strategies such as matching, instrumental variables, difference-in-difference, and synthetic control methods (Miteva et al., 2012; Sills et al., 2015).

While the "counterfactual revolution" (Pearl and Mackenzie, 2018) has certainly delivered clear and quantifiable impacts of initiatives on deforestation trends, it has so far been insufficient in capturing a broader picture of the effects and of why these interventions have worked or not. For example, counterfactual studies have limitations due to data shortages and the effects of complex interactions (Abadie et al., 2015; Baylis et al., 2016). They are also inadequate in understanding implementation dynamics, in particular how implementation (the translation of policies into practice) unfolds (Gueiros et al., 2021) and how actors adjust, shape and bypass existing interventions over time (Carvalho et al., 2019). In this paper, we aim to provide a methodological contribution to the impact evaluation debate by exploring a Bayesian process-tracing approach as an alternative or complementary method to counterfactual studies. This is the first time a Bayesian process-tracing approach has been used to assess interventions designed to halt deforestation.

Process tracing is an increasingly popular method in the Social Sciences to understand causal mechanisms in single-case research designs (Beach and Pedersen, 2013). It aims at testing qualitative explanations of events, usually formulated in terms of entities (actors) engaged in activities, which are interlocked in sequences leading to specific outcomes. These explanations are tested by seeking empirical implications of their existence (or absence); the goal is to find evidence that 'conclusively' shows whether a theory is true or false. This evidence can be categorized according to four famous metaphors (Smoking Gun, Hoop test, Doubly decisive, and Straw in the wind). While there are a few examples of attempts to use this approach to explain deforestation outcomes (Meyfroidt, 2015), process tracing has not as yet captured significant attention in this field. This might be linked to the shortcomings of traditional process-tracing methodologies. While the method is fundamentally underpinned by a Bayesian logic, the reasoning is usually employed informally, and thus fails to account for nuances, providing only limited analytical transparency and replicability (Fairfield and Charman, 2017).

To overcome such limitations, in this paper we use a formal Bayesian process-tracing approach that allows for a more fine-grained assessment of both the strength (probative value) and direction (confirmation or disconfirmation) of evidence; going beyond the four qualitative test categories mentioned above (Befani, 2020a). Since the reasoning employed by the researcher is more transparent with this approach, it can be challenged more easily and updated with additional evidence; while the Bayes formula guarantees the replicability of the operation.

We applied this approach to assess the role of six interventions to halt deforestation that were implemented between 2006 and 2019 in the municipality of São Felix do Xingu, Pará, Brazil. These were selected because they are emblematic cases of longstanding efforts led by multiple state and non-state actors to curb deforestation (Brandão et al., 2020; Schmink et al., 2017; Schneider et al., 2015). The approach allows the testing and comparison of previous studies that investigated similar interventions, including for example the role of credit restrictions (Assunção et al., 2020) and field-based law enforcement (Börner et al., 2015), the creation of protected areas (Barber et al., 2014), as well as commodity agreements (Rajão et al., 2020) and local policies (Sills et al., 2015). In this way, this paper not only provides a methodological contribution but also leverages important insights from domestic and global debates on the effectiveness of interventions to reduce deforestation.

2. Analytical framework

We conceptually distinguish two types of forest loss: (i) frontier deforestation and (ii) deforestation in consolidated areas (Wunder, 2004). The first is the outcome of a frontier expansion process, i.e. the progressive occupation of forestland by newly arrived actors such as colonists, ranchers and firms (Pacheco, 2012). The arrival of these actors triggers a progressive removal of forest resources and conversion to other land uses, mostly pastureland. Frontier expansion typically occurs in stages which are best described by an imaginary line – the front – clashing into virtually intact forests, causing deforestation. This process often generates socio-environmental conflicts with indigenous groups and other forest-dependent communities. The second type of deforestation – in consolidated areas – represents the clearing of forest remnants in post-frontier territories. As the front moves forward to appropriate new lands, the territories behind it begin to consolidate, as tenure rights become more clarified and agricultural land uses evolve towards more intensive production systems (Angelsen and Kaimowitz, 1999).

There are multiple sub-streams of theories which explain both types of forest loss through different lenses and paradigms (Thaler et al., 2019). Overall, deforestation can be explained by a mix of contextual factors and individual motivations. In the case of contextual factors, there are direct and indirect drivers, as well as predisposing factors (Geist and Lambin, 2001). Frontier expansion can be directly driven by colonization processes, land grabbing, infrastructure development and/or agricultural expansion dynamics (Alencar et al., 2004). It can be also shaped by indirect drivers, which are broader social processes such as global commodity prices, the strengthening or weakening of environmental governance, and demographic dynamics. Neither direct drivers (such as new infrastructure developments and the persistence of unsustainable agricultural practices) nor indirect drivers (such as further population increase and changes in global prices) are exclusive to frontier areas; both continue to shape deforestation trends in consolidated areas as well. Predisposing environmental factors or biophysical drivers such as topography, precipitation and soil fertility also influence deforestation trends, both at frontiers and in consolidated areas (Geist and Lambin, 2001).

In the case of individual motivations, the explanation of household decision-making can be summarized by the "needs vs. opportunity" debate. Under this lens, deforestation can be driven by poor households that have no economic alternative to destroying forests, or because landholders and/or squatters are profit maximisers and will seize the opportunity to accumulate more land by moving into forested areas if the perceived benefits outweigh the costs (Angelsen and Kaimowitz, 1999; Babigumira et al., 2014). Considering that it has been more profitable to move into forested areas than to buy lands that have already been cleared, land speculation is a key variable in the Amazonian equation (Azevedo-Ramos and Moutinho, 2018).

3. Case study: São Félix do Xingu

3.1. Occupation process and deforestation frontier

São Félix do Xingu (SFX) is an emblematic and active Amazonian frontier (Alencar et al., 2004; Escada et al., 2005; Schmink and Wood, 2012). The region (see Fig. 1) that is now the municipality of São Félix do Xingu was originally populated by indigenous groups, but since the rubber boom in the late 19th century, other actors such as rubber tappers, fisher people and Brazil nut collectors have started to settle sparsely in the region. It was not until the 1970 s that the region began to face profound landscape transformations. The construction of the PA-279 highway between 1976 and 1983 started to attract migrants from all over Brazil in search of land, thereby creating a deforestation frontier (Schmink and Wood, 2012). Between 1970 and 2000, approximately 32,000 people arrived to the region (Sousa et al., 2016), contributing to the deforestation of 8% of the total municipal area by

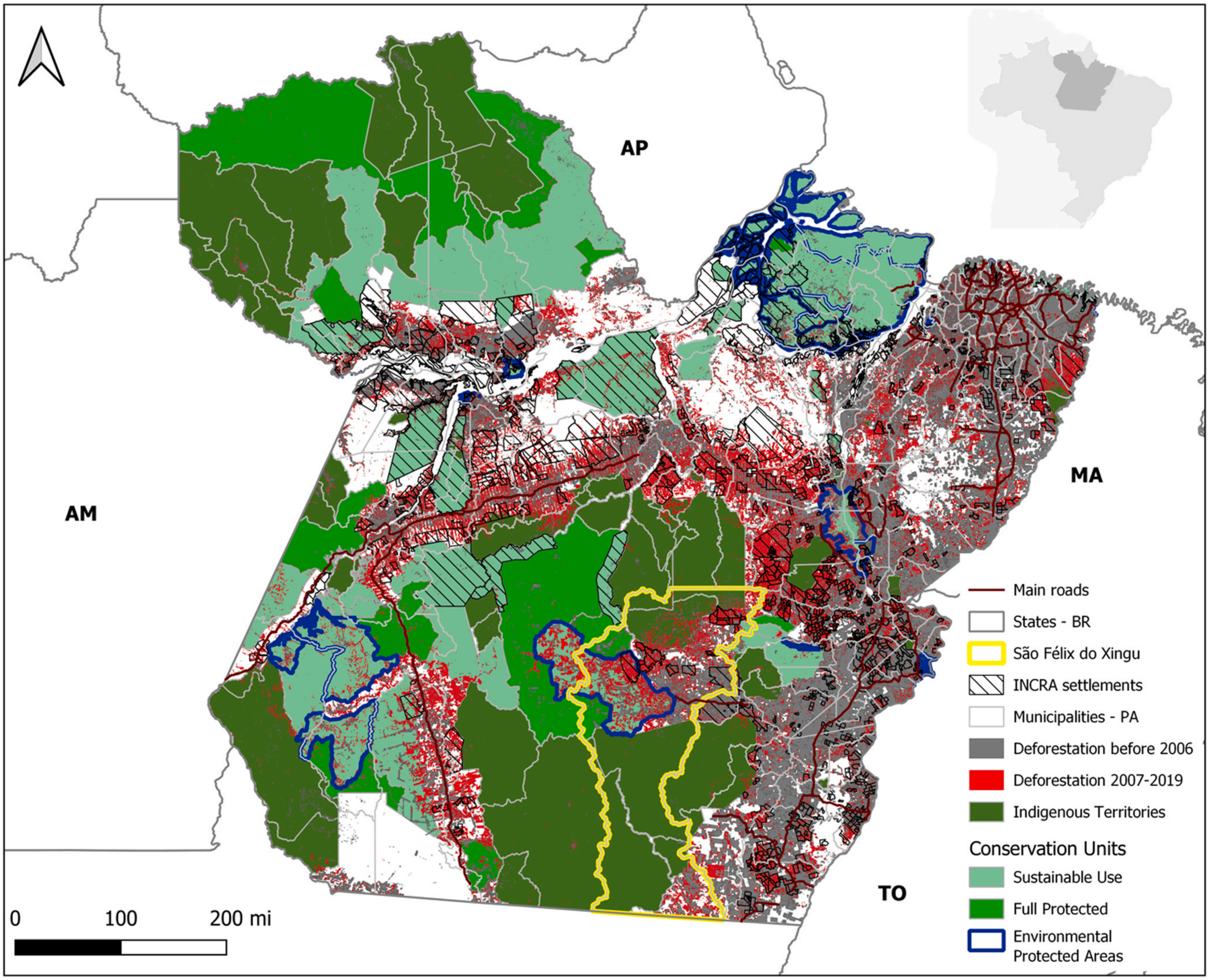

Fig. 1. Location of case study in São Félix do Xingu, Pará, Brazil.

2000 (INPE, 2019). In the following decade, new waves of migrants intensified this process by moving westward into forest areas along the main road and along the unofficial secondary roads that were created (Castro et al., 2004; Mertens et al., 2002). By 2006, the first year of our analysis, the population of SFX was 40,000, and deforestation accounted for 16% of the total municipal area (INPE, 2019). Most population and deforestation dynamics were concentrated alongside the PA-279 road vector, while more remote areas had low population densities and deforestation rates.

3.2. Tenure configuration and environmental regulations

São Félix do Xingu, spanning 8.4 million hectares, is a vast municipality comprising distinct areas. To simplify analysis, we divided SFX into two primary areas: frontiers and consolidated areas. This division is based on frontier expansion geographies and utilized polygons representing different tenure regimes. Frontier areas encompass Indigenous Territories (53%), Fully Protected Conservation Units (6%), and the Environmental Protected Area (APA) Triunfo do Xingu (13%). The first two areas prohibit or impose severe restrictions on deforestation and do not allow privately owned property, operating under distinct environmental regulations. In contrast, APA Triunfo do Xingu represents the least restrictive conservation unit type, permitting private property ownership. These areas typically exhibit high forest cover and attract the attention of land grabbers due to the availability of public lands and low population density. Furthermore, consolidated areas comprise smallholder agrarian reform settlements (6%), directly administered by the Brazilian Agency for Agrarian Reform (INCRA), and the remaining portion of the territory (22%) encompassing areas that accommodate both small and large private properties. These areas typically display reduced forest cover, higher population density, and comparatively stronger consolidated tenure rights. According to the latest agricultural census, SFX holds nearly 6375 properties in private areas, the large majority (75%) owned by smallholders (up to 200 ha); however these represent only 14% of the territory. In contrast, medium-sized properties (200–1000 ha) and large properties (larger than 1000 ha) account for 18% and 7% of the properties and 21% and 65% of the territory, respectively (IBGE, 2017). For these properties, landholders are obliged to maintain a legal reserve, i.e., a proportion of the land that should remain forested (Benatti and Fischer, 2018). In general, private properties must maintain 80% forest cover as legal reserve (the 80% rule), but in certain areas designated as agricultural production zones or consolidated areas, landowners are required to retain 50% forest cover –

i.e., the 50% rule.[1]

3.3. Intervention selection

We selected six interventions implemented between 2006 and 2019 in SFX. The selection was inspired by an updated timeline of forest governance interventions (Brandão et al., 2020) and was cross-checked and triangulated with relevant literature identifying the interventions most likely to reduce deforestation. In Table 1 we introduce these interventions, highlighting their theories of change and characteristics, with related references.

3.4. Deforestation phases

To simplify the analysis we divided the deforestation trend between 2006 and 2019 into three phases. Note that we do not intend to explain every single yearly change in deforestation rates, but rather the general trends over the three phases. These are: (i) a downward change from 2007 to 2010; (ii) stabilization on low deforestation values from 2011 to 2014; (iii) and an upward deforestation trend from 2015 onwards. We did that using municipal deforestation data (PRODES) for the period 2006–2019.[2] Fig. 2 links overall deforestation trends stratified by type of territory with the start date of the interventions selected.

4. Methodological approach

4.1. Theory components building

Our aim is to explain to what extent the abovementioned interventions contributed to shape deforestation trends in each of the three phases. We broke down the theories of change associated with each intervention (Table 1) into nuggets or ‘theory components’.

Theory components (TC) consist of both effects (what happened or didn’t happen) and causal mechanisms (why it happened or didn’t happen). These components are influenced by specific local conditions that triggered, enabled, or hindered the occurrence of those mechanisms. In the context of process tracing, theory components serve as the primary analytical units and form the building blocks of a "composite theory," which represents the overarching explanation (5.4).

The concept of theory components bears resemblance to the notion of middle-range theory explored in other works (Meyfroidt et al., 2018). Each theory component can be seen as a middle-range theory focused on a specific intervention. Similarly, the idea of a composite theory can be seen as a higher-level theory that provides an explanation for interventions aimed at reducing deforestation.

We started with six TC (one per intervention) which in practice were our initial hypotheses or preliminary statements. To build these TC we used data from 15 exploratory interviews in which we asked representatives of local organizations about their perceptions of the effectiveness of the six interventions and why they thought the interventions had contributed in the mentioned ways.

4.2. Data collection

The next step involved the systematic organization of all available data into pieces of evidence. An individual piece of evidence pertains to a specific item, fact, or information that is relevant to any of the

Table 1
Selected interventions.

Intervention name	Theory of change	Characteristics	References
Intervention 1: APA Triunfo do Xingu creation (2006)	Aims at halting frontier expansion by setting aside a specific territory for conservation purposes with more stringent environmental rules, and by clarifying tenure rights. May target both smallholders and largeholders, whose deforesting behaviour is expected to be affected by more stringent rules.	Created as a buffer zone to block westward frontier expansion; Has an intermediary level of protection that allows private ownership of land; Imposes more restrictive land use regulations than non-protected areas in agriculture production zones, including the 80% rule	Barber et al. (2014);Herrera et al. (2019); Nolte et al. (2013);Costa and Reis (2017)
Intervention 2: Strengthening environmental monitoring and enforcement (2008)	Aims at punishing all actors directly involved in deforestation through field-based operations, fines and embargoes; deforesting behaviour is expected to be deterred by harsher punishments.	Led by Brazil’s Environmental Federal Agency (IBAMA) and focuses on field-based operations; Includes the mobilization of state apparatus (military, police, environmental agencies, etc.) to critical regions; Has a deterrent effect by issuing administrative penalties such as embargoes, fines and arrest;[a]	Arima et al. (2014);Börner et al. (2015); West and Fearnside (2021)
Intervention 3: Credit restrictions (2008)	Aims at forbidding access to credit for producers involved in deforestation, and transferring monitoring responsibilities to banks. The actor considering deforestation would thus be deprived from the main source of funding to proceed with deforestation activities.	In 2008, the Central Bank of Brazil adopted rules restricting credit to those who met certain criteria;[b] Smallholders benefitted from less-stringent conditions, including the total exemption of restrictions for the lowest income segment of smallholders;	Assunção et al. (2020)
Intervention 4: Cattle Agreement (2009)	Aims at limiting market access for cattle suppliers involved in deforestation, and transferring monitoring responsibilities to slaughterhouses and meatpackers. The actors are expected to abstain from deforestation because it would	In 2009, cattle buyers signed a legally binding “Terms of Adjustment of Conduct” (MPF-TAC) agreeing to eliminate illegal deforestation from their supply chains;[c] 32 or 70% of all operators have signed the MPF-TAC, including all	Alix-Garcia and Gibbs (2017); Gibbs et al. (2016);Rajão et al. (2020); Armelin et al. (2019)

(continued on next page)

[1] Landholders should also register their properties under Cadastro Ambiental Rural (CAR), a geo-referenced cadastre system that allows public and transparent monitoring of environmental compliance.

[2] As PRODES systematizes annual data for a period of 12 months between August until July (INPE, 2019), specific yearly deforestation rates referred to in this paper reflect the PRODES year (e.g. the 2019 deforestation rate is for the period between August 2018 and July 2019).

Table 1 (*continued*)

Intervention name	Theory of change	Characteristics	References
	create barriers for the sale of their cattle.	major meatpackers with slaughterhouses that buy cattle from SFX;[d] The agreement is monitored via independent audits;	
Intervention 5: Multistakeholder zero-deforestation pact (2011)	Aims at incentivizing local actors (smallholders, ranchers, etc.) to sign zero-deforestation commitments by building participatory development agendas and strengthening public support for forest preservation.	Supported by an EU-funded project;[e] The zero-deforestation municipal pact was signed by 41 entities; A development agenda, developed and monitored through a multistakeholder forum, complemented the pact;	Cisneros et al. (2015);Sills et al. (2015); Brandão et al. (2020)
Intervention 6: Value chain projects (2013)	Aims at disseminating production practices that do not promote deforestation through technological transfer, trainings, certification and premiums in cocoa and beef sectors. Targets both smallholders and largeholders, who are expected to discover and embrace alternative ways to increase profits.	NGOs developed three value chain projects with the explicit goal of halting deforestation; Project 1 targeted the beef sector by engaging ranchers on best management practices; Project 2 incentivized the restoration of degraded areas in smallholder properties through cocoa-based agroforestry systems;[f] Project 3 supported the implementation of best management practices among smallholders and helped some to become certified for organic cocoa production practices;	Garrett et al. (2018);Merry and Soares-Filho (2017); Müller-Hansen et al. (2019); Schroth et al. (2016)

[a] Field base operations became particularly vigorous after the revision of the Environmental Crimes Law in 2008, which introduced new powers and strengthened IBAMA's legal capacity to punish offenders

[b] Criteria include: not being under embargo; holding an environmental license; observing the zoning instrument; and holding a land title. Criteria were originally adopted through the Resolution CMN/Bacen 3.545/2008 (check here). The current criteria for credit were established by Resolution CMN/Bacen 4.883/2020 which include six alternatives to land titles in addition to a CAR registry

[c] In detail, buyers agreed to stopping the supply of cattle from properties on IBAMA's embargo list; not being in an area deforested after 2008; not having Conservation Unit (UC) and Indigenous Territory (IT) overlapping; and not being on the list of areas embargoed under slave labour laws. In order to monitor the agreement, supplier properties must be registered under CAR

[d] These include Frigol S/A slaughterhouses in São Félix do Xingu and Água Azul do Norte, Marfrig Global Foods S/A in Tucumã, JBS S/A in Tucumã; Água Azul do Norte: Frigol; Xinguara: Mercúrio Alimentos S/A, Xinguara Indústria e Comércio S/A. In addition to MPF-TAC, the largest meatpacking companies signed the G4 zero-deforestation agreement with Greenpeace, two of them (JBS and Marfrig) with operations in SFX. Since 2017, Greenpeace has withdrawn from the G4 Agreement in reaction to the irregularities highlighted in the Carne Fria Operation; however, the agreement remains valid for the meatpackers

[e] The "Municipal Pact to Reduce Deforestation in São Félix do Xingu" project, implemented between 2011 and 2014, was led by Brazil's Ministry of Environment (MMA), included the Food and Agriculture Organization of the United Nations (FAO) and several local organizations as partners, and was and funded by the European Union with 6 million EUR

[f] The project implemented demonstration units and raised awareness among smallholder families of agroforestry practices, while facilitating access to markets based on individual producer zero-deforestation commitments

previously identified TCs. It's important to note that Bayesian process tracing accommodates the utilization of both quantitative and qualitative data, making it particularly valuable when data sources are scattered and incomplete. To build our database of individual pieces of evidence we used four types of data. The first was a (i) detailed deforestation analysis. We broke down deforestation figures to reflect the tenure configuration (or frontier status) by adding a layer to deforestation polygons that comprised the tenure configuration of the territory, which included five tenure categories (see 3.2). We also assessed actor contributions to deforestation rates over time, by breaking down deforestation figures at the property level within the 2 categories that allow private properties: (i) non-special areas and (ii) APA Triunfo do Xingu. That analysis was done using the CAR public database downloaded in 2019. Given the spatial configuration of SFX, we consider APA Triunfo do Xingu and Indigenous Territories as frontiers, and settlements and non-special areas as consolidated areas.[3]

The second type was (ii) quantitative data for proxy-indicators of the ʻyearly intensityʼ of selected interventions collected at municipal level systematized on a yearly basis. For interventions 2 and 3, we were able to collect suitable data (i.e. the number of credit contracts per year and number of embargoes per year). For the remaining four interventions, we were not able to find similar proxies. Additionally, we collected data on biophysical and socioeconomic variables that are typically used to explain deforestation in order to test alternative hypotheses (Rosa et al., 2013) – meaning hypotheses that do not address the interventions included in the primary hypotheses: in this case, beef prices and precipitation.[4] Since our analysis is at the municipal level (Hargrave and Kis-Katos, 2013), we were not able to find suitable panel data on topography, soil fertility and distance to roads.[5]

The third type was (iii) quantitative and qualitative data available in secondary sources such as governmental websites, official legislation, project reports, newspapers, grey literature, internal documents, and peer-reviewed articles.

Finally, we used (iv) qualitative data collected through a series of 38 semi-structured interviews with key informants, including the above-mentioned 15 exploratory interviews. Interviewees were selected via snowball sampling, by asking in the municipality to identify key players for each of the six interventions. Respondents were asked to explain their role in the process, assess the relevance of specific initiatives, and share their overall perceptions of changes observed. We reached 'saturation' by interviewing representatives of smallholders (9), ranchers (5), municipal agencies (8), state and federal agencies (3), non-governmental organizations (NGOs) (10), and private sector and banks (3). We paid particular attention to memory recall biases by

[3] In the particular case of SFX, Conservation Units and Indigenous Territories are located in the west, in theory working as a buffer zones to block westward frontier.

[4] While soy and timber prices are considered important indicators, these were not included since they are not relevant economic activities in the municipality.

[5] The most recent available dataset on secondary roads is from 2012.

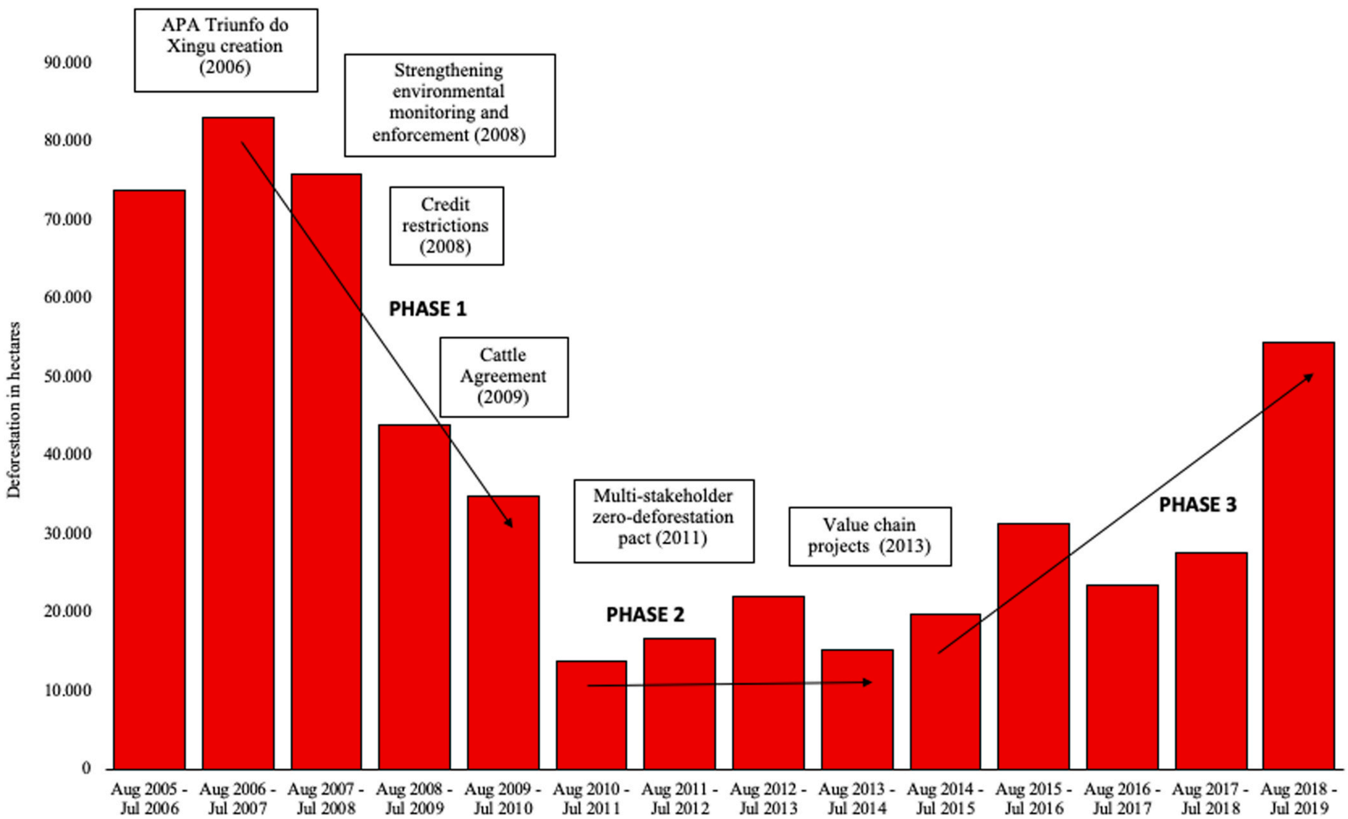

Fig. 2. Deforestation phases.

carefully triangulating perceptions from different actors and other available sources of data. Altogether, we were able to systematically organise the raw data into 31 individual pieces of evidence.[6]

4.3. *Testing theory components*

4.3.1. *Traditional vs Bayesian Process Tracing*

In traditional, 'informally Bayesian' Process Tracing, the researcher categorises evidence according to two dimensions: direction (whether it strengthens or weakens the theory) and strength (whether it is weak/inconclusive or strong/conclusive for the theory). The four metaphors used to 'label' the pieces of evidence are associated to 2 × 2 combinations of these dimensions: the Smoking Gun conclusively strengthens the theory but is unable to weaken it by itself; the Hoop test conclusively weakens the theory but is unable to strengthen it by itself; the Doubly decisive is conclusive in both directions and the Straw in the wind is always inconclusive. Despite its growing popularity, this approach misses the nuances of seemingly contradictory or complex evidence packages, for example when some observations strengthens the theory and others weaken it; and it also less transparent in the sense that it is more difficult for the reader to reconstruct or comprehend the reasons why a certain observation has been deemed strengthening or weakening.

The formally Bayesian approach overcomes this limitation by employing the Bayes formula to estimate confidence levels in a series of claims or theory components. This approach begins by assigning a standard probability value, typically 0.5, which represents the initial confidence level that a certain theory is true before the observation of empirical evidence. This value is known as the "prior confidence." Then, researchers need to estimate two probabilities: sensitivity and Type I error. Sensitivity refers to the probability or likelihood of observing the associated piece of evidence under the assumption that the theory component is true. On the other hand, Type I error represents the probability or likelihood of observing the same evidence under the opposite assumption (that the theory component is false). These estimates play a crucial role in the formal Bayesian approach, differentiating it from the informal process tracing method. Rather than simply labeling evidence as a "smoking gun" or a "hoop test," discussions among the researchers are conducted to derive these probability estimates, the ratio of which represents a measure of the probative value or "strength" of the evidence.[7] This approach is more rigorous because it allows other researchers to easily replicate (and challenge) the assessment process and produces a quantitative assessment of the strength of evidence.

4.3.2. *Formal assessment step 1: calculating posterior values for individual evidence*

The estimation of both sensitivity and Type I error is crucial to the entire process. In order to remove any preconceptions or biases about the theories and allow the evidence to speak for itself, we start with a prior probability distribution of 0.5 (Befani and D'Errico, 2020). It is important to note that these estimates of sensitivity and Type I error are provided by the researchers themselves and reflect their logical understanding of the subject matter. With these estimates in hand, the next step is to calculate the probability, known as the "posterior confidence,"

[6] Please note that data was collected in different moments as part of the iterative process.

[7] Namely the so-called "likelihood ratio", obtained as the ratio between Sensitivity (numerator) and Type I Error (denominator).

that a given theory is true after the observation of empirical evidence. This calculation is performed using the Bayes formula,[8] which yields a value between 0 and 1 representing the posterior confidence. In other words, it quantifies the level of confidence one should have in the theory component after observing the associated evidence.

It is fair to say that if estimates change, the posterior confidence will also change. However, depending on which of the two values changes and on the extent of this change, the range of variation of the posterior can vary from negligible to substantial: in other words, if the reader or another researcher does not agree with the estimates and the reasoning behind it, they can use the value that seems reasonable to them and check to what extent this affects the value of the posterior confidence. For example, if the evidence the strength of which we are assessing is observed rather than not observed, even large changes in the sensitivity usually only have negligible consequences on the posterior confidence, while smaller changes of the Type I error sometimes affect it to a large extent. While we cannot claim that our estimates are "the absolute truth" and represent a consensus in the community, the transparency of the methodology allows anyone to question the reasoning behind our estimates and propose their own; and the formula will tell us whether this difference leads to fundamentally different findings.[9]

4.3.3. Formal assessment step 2: calculating posterior values for evidence packages

Once we have posterior confidence values for all individual evidence, we can move on and assemble individual pieces into a package – the so-called evidence package or, in other words, a cluster of evidence that can strengthen or weaken a specific theory component.[10] The literature (Befani, 2020b) suggests a series of possible procedures to achieve this. In our case, we organised the evidence so that some pieces could be considered stochastically independent in relation to a single theory component[11] (which means that observing the first one does not change the probability of observing the next one, conditioned on the TC being true or false).

So we applied the related formula (Befani, 2020b)[12] to obtain the overall sensitivity and Type I error values for the entire evidence package associated to that theory component. This formula is based on probability algebra, according to which the probability that two independent events both take place is the product of the probabilities of the single events. When the pieces of evidence did not seem independent to us, we assembled them into a single, complex observation, and recalculated the Sensitivity and Type I error for that single, more complex observation (in other words, the probabilities of directly observing the whole package). Once these were available, we applied the Bayes formula (the same applied for individual pieces of evidence) and directly obtained the posterior (continuing to use 0.5 as a prior).

This procedure was done iteratively which in some cases led to collecting new evidence and refining some theory components until we could not find any additional evidence that we could logically add. The assessments were also iteratively compared against each other to ensure consistency among the estimates; or in other words, to ensure that similar events had been assigned similar probabilities; and that comparatively more probable events had been assigned proportionally higher ones. Note that, in order to avoid confirmation bias and in line with good process tracing practice, we searched for evidence that could either strengthen or weaken the theory, or that had either high sensitivity (so high enough power to weaken the theory) or low Type I error, so high enough power to strengthen the theory).

Finally, we should mention that most often we started from a qualitative descriptor for the confidence level (for example, "more likely than not") and then we used the conversion rules of Table 2 to translate this into a numerical value (usually selecting the middle point unless our description leaned towards one of the two extremes). In presenting the findings, we converted the posterior probabilities (back) into qualitative descriptors of confidence.[13]

5. Results

5.1. Final results for all theory components

Table 3 provides the final results. In total, we developed nine theory components spanning three periods of time, which included causal mechanisms explaining their success or failure as reflected in the above trends. For each component, we identified both the effect and the mechanism. We are practically certain that four theory components are true and reasonably certain that two components are true. We are also highly confident that two other theory components are true and only cautiously confident that one component is true.

5.2. Detailing formal assessments of evidence and theory components

In this section, we present the analysis for TC1 and TC2.1 only. The complete analysis is provided in Annex 1.

Table 2
Translation between confidence levels and ranges / numerical intervals.

Qualitative descriptor of confidence level	Low end	High end
Practical certainty that () is true / observed	0.99	1
Reasonable certainty that () is true / observed	0.95	0.99
High confidence that () is true / observed	0.85	0.95
Cautious confidence that () is true / observed	0.70	0.85
More confident than not confident that () is true / observed	0.50	0.70
Neither confident nor not confident that () is true / observed (or false / not observed) – no idea	0.50	
More confident than not confident that () is false / not observed	0.30	0.50
Cautious confidence that () is false / not observed	0.15	0.30
High confidence that () is false / not observed	0.05	0.15
Reasonable certainty that () is false / not observed	0.01	0.05
Practical certainty that () is false / not observed	0.00	0.01

Source: Adapted from Befani (2020a)

[8] The posterior in the Bayes formula is given by the following ratio: the numerator is the product of the prior and the sensitivity; while the denominator is the sum of the latter product (prior times sensitivity) and the product of the inverse of the prior times the Type I Error. In symbols: P(theory true | evidence E observed) = [prior*P(evidence E observed | theory true)] / [prior*P(evidence E observed | theory true) + (1-prior)*P(evidence E observed | theory false)].

[9] For reasons of space we are unable to provide additional guidance on how to apply the methodology, and we refer the reader to the suggested literature. The following is an extensive step-by-step "manual" with several practical examples https://eba.se/en/reports/cridible-explanations-of-development-outcomes-with-bayesian-theory-based-evaluation/17287/

[10] Please note that each evidence package is connected to a single theory component.

[11] This was discussed internally in the research team.

[12] In symbols: P(A AND B) = P(A)*P(B|A) and P(B)*P(A|B). If A and B are independent, it means that P(A|B) = P(A) and P(B|A) = P(B). If we replace P(B|A) with P(B) and P(A|B) with P(A) in the previous equations, we obtain P(A AND B) = P(A)*P(B) = P(B)*P(A).

[13] When assembling independent pieces of evidence, it is advisable to settle on a point estimate within the interval (usually the mid-point or close to it) to reduce the complexity of the calculations. In our description of the estimates, we sometimes use 'neither likely nor unlikely' or 'as likely as not' to describe the mid-confidence point and 'more likely than not' for the levels immediately before and after. We also use 'highly likely' interchangeably with 'high confidence' and often use the 0.9 mid-point to quantify this estimate.

Table 3
Summary of the formal assessment.

Theory Component	Hypothesis	Posterior (from 0.5 prior)	Qualitative assessment
TC1	Intervention 1 (APA Triunfo do Xingu creation) did not significantly shape deforestation rates in phases 1 (2007–2010), 2 (2011–2014) and 3 (2015–2019). The reason was in part due to poor implementation and poor local acceptance.	**0,86**	High Confidence
TC2.1	Intervention 2 (Strengthening environmental monitoring and enforcement) was effective in phases 1 (2007–2010) and 2 (2011–2014). The causal mechanism for this was initially the deterrent effect of a specific field-based operation (Operation Boi Pirata), and this effect was maintained through the use of command-and-control instruments such as embargoes.	**0,99**	Practical Certainty
TC2.2	Intervention 2 (Strengthening environmental monitoring and enforcement) lost effectiveness in phase 3 (2015–2019). On the one hand due to diminishing intensity of operations; and on the other hand environmental crime became more complex to target.	**0,92**	High Confidence
TC3.1	Intervention 3 (credit restrictions) were effective in phases 1 (2007–2010) and 2 (2011–2014), particularly among medium-to-large landholders. It became more difficult to lend money to rural activities, and bank monitoring systems improved.	**0,98**	Reasonable Certainty
TC3.2	Intervention 3 (credit restrictions) continued to be effective in phase 3 (2015–2019). It remained difficult for proponents of rural activities to borrow money, and bank monitoring systems continued to improve.	**0,95**	Reasonable Certainty
TC4.1	Intervention 4 (Cattle Agreement) reduced deforesting behaviour in medium-to-large landholders particularly in phase 1 (2007–2010). Created market pressure by establishing environmental criteria for slaughterhouses to buy cattle from ranchers that were mostly reliant on cattle revenue. Moreover, it required ranchers willing to sell to slaughterhouses to enter the CAR system, which was the first step to accepting legality.	**0,99**	Practical Certainty
TC4.2	Intervention 4 (Cattle Agreement) was not effective at reducing deforestation in phase 3. This intervention lost effectiveness over time as deforesters found new ways to circumvent the rules.	**0,99**	Practical Certainty
TC5	Intervention 5 (multistakeholder zero-deforestation pact), which ended in 2014, managed to engage smallholders and reduce deforestation among them in phase 2 (2011–2014). This created an optimistic mindset around building a development model delinked to deforestation, and promised incentives and benefits for non-deforestation behaviour.	**0,71**	Cautious Confidence
TC6	Intervention 6 (value chain projects) did not effectively prevent smallholders from deforesting in phase 3 (2015–2019). When the multistakeholder project ended in 2014, it was not replaced by an intervention that effectively engaged a meaningful share of smallholders. Moreover, these projects did not manage to keep deforestation rates low among participants.	**0,99**	Practical Certainty

5.2.1. Theory component 1 (TC1)

Our initial hypothesis was that APATX would decrease deforesting behaviour (in both small and largeholders) by making a relevant set of rules clearer and more stringent. However, the evidence showed that this influence was quite unlikely to have materialized, which led us to try to identify alternative hypotheses that would fit the evidence better so that we could measure its likelihood more rigorously using the formal Bayesian testing. Our most strongly supported hypothesis was the following (presented above in Table 3):

TC1: APA Triunfo do Xingu (APATX) did not significantly shape deforestation rates in phases 1, 2 and 3. The reason was in part due to poor implementation and poor local acceptance.

TC1 is associated with two independent pieces of evidence: one showing how slow implementation had been, and another one indicating that acceptance of the new rules had been very low among the targeted actors. We estimated the likelihoods of observing these pieces of evidence (separately) under the two assumptions that the theory component is true (sensitivity) and false (Type I error). For both pieces of evidence, the former is higher than the latter, which means that the evidence is more likely to be observed if the theory is true than if it is false (Table 4). The motivation/reasoning behind the estimates is explained in Table 4; for example, if the theory was false and the intervention did significantly help reduce deforestation rates, it seems unlikely that it was poorly implemented (Type I error for the first piece of evidence)? Or, if the theory is true and the intervention had negligible effects, how likely is it that the relevant actors would not accept it (Sensitivity of the second piece of evidence)? Somewhat likely because it is not very easy to imagine this intervention not being successful if the locals do accept it. As mentioned earlier, our goal was to make the process transparent so that readers can compare their own estimates to ours and see how much the final results change.

Once the values are estimated, the Bayes formula would need to be used for the posterior to be calculated for the whole theory component. The final result (as presented in Table 3 together with the remaining 8 components) is 0.86, i.e. highly confident that TC1 is true.

5.2.2. Theory component 2.1 (TC2.1)

For the TC2, our initial hypothesis was that the harsher punishments would deter deforesting behaviour and we found six pieces of evidence (Table 5) which – to varying degrees – all seemed to confirm it. In particular, we found that the initial effect was maintained by command and control instruments, and thus we incorporated this notion into the

Table 4
Evidence collected and assessed for TC1.

Evidence N	Evidence	Sources	Sensitivity estimate		Type I error estimate	
			Motivation	Value	Motivation	Value
Evidence 1.1	Slow implementation of APATX main instruments. The management council was created in 2011, just five years after the instituting decree. By 2020, the management plan was yet to be approved. By 2019, only 5% of APATX (114 properties) were formally titled.	Government website, official decree and Pará Land Institute (ITERPA) official data	If the intervention did not reduce deforestation rates, it is slightly more likely than not that implementation would lag behind; confidence is not higher because there could be other reasons / mechanisms why the intervention didn't work.	0.6	If the intervention worked and was responsible for the reduction of deforestation rates, it is unlikely that it was poorly implemented.	0.2
Evidence 1.2	Poor local acceptance of APATX. The 80% rule was never accepted by local actors. Changing the rule back to 50% has been a frequent request by local actors, ranging from local politicians to smallholders.[a]	Management council meeting notes and interviews in 2017–2018	Cautious confidence: if APATX did not succeed in decreasing deforestation, it is likely that locals did not accept it; evidence of local acceptance would weaken the theory that the intervention was ineffective.	0.8	If APATX is effective, it would not necessarily be because locals accepted it; decreased deforestation could have been a result of penalties. Still, it is more likely than not that if a restrictive rule is respected by local actors, it is accepted by them.	0.4

[a] Local politicians and ranchers have raised this several times and issued a specific request to the governor of Pará

Table 5
Evidence collected and assessed for TC2.1.

Theory component 2.1:						
Evidence 2.1.1	The Ministry of Environment of Brazil said in a public interview that Boi Pirata was a strong signal and a determinant step to tackle deforestation in the Amazon.	Public interview to newspaper	It is more likely than not that the Ministry would mention this publicly if the theory is true, since it was the first operation held in the territory since the revision of the Environmental Crimes Law in 2008, and the first one that authorized the seizure of illegally raised cattle.	0.6	A Ministeŕs opinion is not technical, so it would have been difficult for him to assess with precision if *Boi Pirata* or an alternative hypothesis caused decreased deforestation. As politicians are driven by political motivations, it is possible that he overestimated the role of his Ministry and tried to gain credit for deforestation reductions.	0.4
Evidence 2.1.2	Several ranchers removed cattle from their properties at APA during Operation Boi Pirata, which showed they were frightened by the measure.	Website news (confirmed by several media sources)	It is highly likely that an effective operation would scare ranchers away and protect their investments by moving their cattle away from APATX (see section 5.4.2).	0.9	It is highly unlikely that several ranchers would have removed hundreds of cattle heads from their properties at the same time without Operation Boi Pirata. We could not find other reasons that could justify this behaviour.	0.2
Evidence 2.1.3	Operation Boi Pirata is the only individual field-based operation mentioned by interviewees as relevant and is considered an important landmark by ranchers and NGO representatives.	Personal interviews	If the theory is true that Boi Pirata was effective, we do not necessarily expect interviewees to mention it.	0.5	There is no particular incentive or hidden agenda for people to mention this specific operation. Yet perceptions of local actors could be wrong. Perhaps there is a dominant narrative of the relevance of Boi Pirata that was replicated among specific groups such as ranchers and NGO representatives.	0.3
Evidence 2.1.4	Operation Boi Pirata targeted only medium-to-large landholders at the frontier.	Website News and deforestation data	By targeting medium-to-large landholders, we would have expected Boi Pirata to result in a decline in deforestation rates within this group of actors, with a smaller decline (or no decline) in other groups. This is what happened.	0.9	The specific targeting of medium-to-large landholders does not necessarily mean that the intervention was effective in this group.	0.5
Evidence 2.1.5	There is a significant relationship between the number of embargoes and deforestation rates between 2005 and 2019, suggesting a causal relationship between intervention 2 and deforestation rates (Adjusted R-squared: 0.5453). For every additional embargo, 459 ha of forest were saved ($p = 0.01545$ **).	Linear regression	If improved environmental monitoring and enforcement was effective, it is highly likely that it significantly relates to deforestation rates.	0.9	Correlation is not causation. There could be confounding variables explaining the decrease in deforestation. However, we ruled out several alternative explanations that could be responsible for this correlation, including precipitation (no significant relationship) and beef prices (negative relationship).	0.3
Evidence 2.1.6	Environmental monitoring and enforcement intensified in 2011. The two highest peaks of annual embargoes coincide with the two lowest annual deforestation rates.	IBAMA data	It is highly expected that deforestation rates would respond/react to the intensification of command and control.	0.9	It is very unlikely to observe such trends if the theory is false. There could be still confounding variables, but this would be very unlikely to occur twice.	0.3

theory we tested:

TC2.1: Improved environmental monitoring and enforcement (intervention 2) was effective in phases 1 and 2. The causal mechanism for this was initially the deterrent effect of a specific field-based operation (Operation Boi Pirata), and this effect was maintained through the use of command-and-control instruments such as embargoes.

After the assessment of individual pieces of evidence, we checked for independence, and realized that 2.1.2 and 2.1.3 were not fully independent. Instead of grouping both into a single piece and reformulating its description, we dropped 2.1.3 because – although it would further strengthen the theory – we were already satisfied with the extent to which we thought the overall package would strengthen the theory. At this point, we inserted the estimated values (sensitivity and Type I error for each single piece of evidence) into the electronic sheet we used for the calculations. As presented in Table 3, the confidence of theory component 2.1 being true was practical certainty (0.99).

5.3. Composite theory

5.3.1. What explains the decrease in deforestation rates in phase 1 and its stabilization in phase 2?

The first part of our updated theory is that interventions 2 (0.99, TC2.1), 3 (0.98, TC3.1) and 4 (0.99, TC4.1) are causally responsible for the decisive downward deforestation trend described in phase 1, while intervention 1 did not play a role (0.86, TC1). We found no additional economic, political or biophysical factors that might have caused such a drop in deforestation rates.[14]

We can think of the simultaneous existence (or simultaneous effectiveness) of interventions 2, 3 and 4 as an obstacle race that deforesting actors participate in, where the first obstacle represents improved environmental monitoring and enforcement, the second represents credit restrictions, and the third, market pressure via the Cattle Agreement. These three interventions changed the incentive structure of decision-making both at the frontier and in consolidated areas. They targeted particularly medium-to-large actors (deforestation reductions were swifter in APA and non-special areas [−58% and −65%] and most reductions in absolute area [−92%] were obtained from medium-to-large landholders). They strengthened deterrents for deforesters, who experienced a 'shock' psychological effect from penalties. The threat of sanctions and punishment for medium and large holders was widely perceived as real, and it made deforesters pause or reconsider their expansion strategies in order to avoid losses. Their incentives and opportunities to deforest were attacked on all fronts: if they could survive law enforcement, they could not access credit; if they managed to survive both, they still faced the slaughterhouses' embargo.

The mechanisms behind these interventions were the following. First, the revision of the Environmental Crimes Law in 2008 worked as a 'stick', introducing new powers and strengthening IBAMA's legal capacity to impose penalties, including the ability to seize goods involved in criminal activities. Boi Pirata was the first operation held in the territory after the law was revised, and it was the first time that environmental enforcement caused economic losses to deforesters, in particular medium-to-large landholders. Second, landholders started to face credit restrictions, which significantly reduced their capacity to access capital and consequently to deforest. Third, the Cattle Agreement worked as a 'carrot', creating market pressure by establishing environmental criteria for slaughterhouses in the procurement of cattle. As ranchers were entirely reliant on cattle revenue, this was a very powerful obstacle. Fourth, the Cattle Agreement required ranchers willing to sell to slaughterhouses to enter in the CAR system, which was the first step to accepting legality. Until that moment, ranchers were very reluctant to adhere to CAR, since this was the most important instrument to promote transparency and strengthen monitoring controls. Although evidence related to the later stages of the process suggests that the Cattle Agreement was not effective (TC4.2), we posit here that the Cattle Agreement was effective during its initial stages (TC4.1).

In set-theory terminology, we can also think of our theory as a logical union, where at least one of these interventions is causally responsible for the widespread behavioural change that resulted in the downward trend in deforestation. In other words, we do not know if the runner stopped at the first obstacle, or at the last one, or if they stopped for a moment at the first and then continued and stopped again at the second; but we believe that at least somewhere along the way one of these obstacles changed their behaviour and was consequential. We calculated the probability that deforesters have managed to resist all three types of incentives for behavioural change in the period, as the product of the probabilities of avoiding each one of them: the result is infinitesimally small, while its inverse – the probability that deforesters' behaviour has changed as a consequence of at least one type of these incentives – is 0.999997. The probability that all three interventions worked at the same time is also quite high (0.95) (Annex 1).

In addition to the three abovementioned interventions, we also posit that intervention 5 offered additional pressure to tackle deforestation among smallholders in phase 2 (TC5). Contrary to phase 1, substantial deforestation reductions were achieved in settlements (−34% in phase 2 vs +6% in phase 1) and among smallholder properties (−41% in phase 2 vs −26% in phase 1). Although our confidence is not as high as for the previous part of the theory, we are still cautiously confident that this has occurred (0.71, TC6). If this part of the theory is true, we could explain that previous 'stick' interventions were further complemented by a multistakeholder process which created an optimistic mindset around building a development model delinked to deforestation. During this period, SFX became a well-known site, and case study, of successful efforts to reduce deforestation, and this created a sense of achievement. This intervention worked as a 'carrot' and managed to significantly engage smallholders, who were promised incentives and benefits for their non-deforestation behaviour.

5.3.2. What explains the upward change in phase 3?

When discussing the reasons behind the substantial decrease in deforestation rates in phase 1, we concluded the three abovementioned interventions were highly likely to be the causes. Therefore, if we are faced with the task of explaining the trend reversal, we first check if the three interventions were still working in phase 3 as they did earlier. We found that, indeed, they were not; in particular, from a prior of 0.5, we obtained practical certainty (0.99) that intervention 4 was less effective at inducing non-deforesting behaviour (TC4.2), as well as high confidence (0.92, TC2.2) that intervention 2 was less effective. As for intervention 3, we are reasonably confident that it continued to work (0.95, TC3.2), so it cannot be held responsible for the trend reversal.

Therefore, we can conclude that the 'stick' strategies lost impetus, which led local actors to gradually resume their deforestation activities, particularly at the frontier, as expanding into new lands became less risky. In this phase, the relative importance of deforestation at APA grew to nearly 50% of total municipal deforestation, while deforestation in Indigenous lands observed a sharp increase, representing nearly 20% at the end of phase 3.[15] There are several factors explaining why the previous mechanisms lost effectiveness. First, environmental monitoring and enforcement became less effective, on the one hand, due to diminishing intensity of operations; on the other hand, environmental crime became more complex to target. As deforestation developed through organized crime in phase 3, including the adoption of sophisticated strategies and legal artifices, previous field-based operations were not as effective as in the past and IBAMA could not replace them by equally

[14] During this period (in May 2012), Brazil approved a revised version of the Forest Code. However, we found no evidence of a meaningful role for the Forest Code Revision in maintaining low deforestation rates during this time.

[15] Deforestation in non-special areas observed relatively minor increases, while deforestation in INCRA settlements is relatively stable in phases 2 and 3. At the end of phase 3 the total percentage of forest cover among settlements was below 20%, which indicates that forest reserves in these territories were already near exhaustion.

effective alternative strategies.[16] This was particularly important for the rise of frontier deforestation, which is grounded on speculative behaviour. Second, the Cattle Agreement also lost effectiveness over time, as deforesters found new ways to circumvent the rules and as slaughterhouses started to find loopholes to bypass it (Carvalho et al., 2019). This includes: the lack of effective cattle traceability systems (thereby allowing animals from embargoed farms to be incorporated into the herd sold to slaughterhouses); landholders splitting CAR registration into two different areas, one with illegal deforestation and the other used for trading; and the use of leased legal rural properties for 'cattle laundering'.

Finally, we assessed the role of intervention 6 and concluded with practical certainty that it was not effective (0.99, TC6). With the end of the main project supporting intervention 5 in 2014, the development agenda was seriously affected.[17] As it was gradually replaced by value chain projects to promote sustainable agricultural practices, the 'carrot' component also lost effectiveness. Value chain projects were not effective at changing participant behaviour. We assume with high confidence (0.86, TC1) that intervention 1 continued to be ineffective in phase 3, since no additional evidence was found for this period. We also found no evidence of the role of external factors such as beef prices or climatic variables such as precipitation, in particular for this phase. During this period (2014–2019), we identified two external factors that might have contributed to shaping deforestation rates, mostly at frontier areas. First, Brazil started a convoluted political process under which environmental issues became less relevant. This began with the impeachment of the country's president in 2016 and gained impetus with the 2018 election of a new government that espoused a strong anti-environmental rhetoric, encouraging deforestation (Oliveira et al., 2023). Second, the situation in the Apyterewa Indigenous territory became more unstable in 2018, with political decisions favouring encroachers, leading to skyrocketing deforestation.[18]

6. Implications for deforestation debates

6.1. The role of protected areas

There is a growing body of evidence and a relative consensus regarding the overall effectiveness of protected areas in reducing deforestation (Gonçalves-Souza et al., 2021). However, the discussion becomes more nuanced when we consider differentiating among types of protected areas based on private property rights, intensity of government enforcement, and existing deforestation pressure. This distinction is particularly relevant when examining protected areas located in frontier regions (Pfaff et al., 2015). Our findings, although with a moderate degree of likelihood (0.86, TC1), support the theory that less restricted protected areas, such as APA, are not effective in curbing deforestation at deforestation frontiers, as suggested by others (Carranza et al., 2014; Jusys, 2018).

Several factors contribute to this lack of effectiveness. Firstly, APAs are not representative of protected areas in general, and their level of protection is generally low. Additionally, inadequate conservation investments, including limited resources for staff, equipment, stakeholder collaboration and management plans (Nolte et al., 2013), further hinder the implementation of management instruments, which are crucial for increasing the effectiveness of protected areas in reducing deforestation (West et al., 2022; Soares-Filho et al., 2023). Furthermore, addressing the primary driver of deforestation in these territories, namely land tenure conflicts and intruders claiming land ownership, requires political and enforcement capacity (Fearnside, 2017). Instituting less restricted protected areas in deforestation frontiers without considering these crucial elements is unlikely to effectively address deforestation issues.

6.2. The role of environmental monitoring and enforcement

Our findings on the role of law enforcement and field-based operations indicate that these interventions are effective (0.99, TC2.1). They play a particularly pertinent role in frontier areas, where incentives or 'carrots' are less likely to be effective, and when complemented with other 'stick' interventions. As mentioned elsewhere, we support that traditional conservation strategies are a good option to halt deforestation (Soares-Filho and Rajão, 2018). This analysis also confirms findings that command and control is more effective among largeholders (Godar et al., 2014). Still, implementation issues and adaptive management can be problematic in these type of interventions, which may be well implemented for a certain period but can lose effectiveness over time (0.92, TC2.2). This likely relates to the 'stick' nature of these interventions, as they normally require the deployment of significant amounts of financial resources and political capital in addition to monitoring of embargoed areas, which is difficult to maintain in the long term (Silva et al., 2022). It is also likely that targeted groups will find ways to circumvent systems, so these interventions need to be constantly monitored and evolve to adapt to shifting causes of deforestation and mechanisms. In particular, since deforestation in frontiers has become associated with complex organized crime and less with typical migration processes (Trancoso, 2021), environmental monitoring and enforcement that focus more on the 'bottom' of deforestation activity rather than on the more complex criminal chain (i.e., 'follow the money') are less likely to be effective.

6.3. The role of credit restrictions

Our findings indicate that credit restrictions had long-term effectiveness (0.98, TC3.1), confirming previous findings (Assunção et al., 2020). We also found that credit restrictions, as implemented in the Brazilian Amazon context, are less likely to be circumvented than law enforcement and field-based operations (0.95, TC3.2). One possible reason is that banks' internal monitoring systems have evolved more effectively than government strategies; another might be the fact that banks have local agencies in the targeted municipalities and are able to monitor more closely their debtors. However, credit restrictions are probably limited to the extent that people rely on banks or until they find other funding sources to continue deforestation activities. Since frontier deforestation is increasingly connected to organized crime, it is likely that funding for these activities is obtained through non-traditional credit services.

6.4. The role of commodity agreements

Our findings indicate that commodity agreements in the beef sector can be effective solutions for a period of time (0.99, TC4.1), but they need to be constantly adapted to new circumstances. It is likely that targeted groups will find ways to circumvent rules, so these agreements need to be constantly monitored and refined (0.99, TC4.2). These

[16] In phases 1 and 2, IBAMA operated under a strategy of deterrence that used headline-making punitive operations to send a clear message that the federal government was no longer tolerating deforestation. As deforestation developed through organized crime in phase 3, including the use of sophisticated strategies and legal artifices, IBAMA switched its strategy to intelligent operations aimed at specific targets, including money laundering and political corruption. Carne Fraca and Carne Fria operations are examples of that new modus operandi. However, the loss of momentum in environmental control at a national level has severely limited IBAMA's capacity to maintain such operations.

[17] Local actors and NGOs tried to reestablish the agenda by instituting alternative strategies, such as the Municipal ABC Plan in 2016; however, this plan was not actually implemented or appropriated by local actors, in part due to changing local government.

[18] Disputes over the Apyterewa Indigenous Land date back to its initial demarcation in 1987, with legal complexities and increasing tensions between the Parakanã people and encroachers continuing to date.

findings align with existing literature on the challenges of targeting indirect suppliers (Rajão et al., 2020). While promoting traceability among major meatpackers can exert additional pressure and discourage certain suppliers, and linking traceability with premium instruments can incentivize non-deforestation behavior, these agreements may only reach well-connected suppliers who have already cleared most of their lands and are less prone to continued deforestation. Non-compliant suppliers can sell cattle in local unregulated markets or to smaller companies lacking stringent or any monitoring systems. As beef-related deforestation typically occurs on a minority of properties, often in remote areas near frontiers with higher forest cover (Skidmore et al., 2021), targeting major meatpackers, supermarkets, and export countries is unlikely to reach these groups. Instead, wider adoption by medium and smaller buyers (Levy et al., 2023) and enhanced monitoring systems covering indirect suppliers and auxiliary properties could enhance effectiveness (Skidmore et al., 2021).

6.5. The role of multistakeholder processes

Our findings on the role of multistakeholder processes were not strong, so we can only carefully propose some generalizations (0.71, TC5). In principle such processes can be effective to target smallholder-driven deforestation, but they need to be realistic about concrete achievements and must manage local expectations. Challenges include: the need to engage authorities at higher administrative levels with the capacity to target structural local problems such as tenure clarification; having the necessary time and resources to keep the process dynamic; and having an adaptive structure that is able to survive project or electoral cycles. This supports previous research on the topic (Sarmiento-Barletti et al., 2020). An important element on the role of multistakeholder platforms is whether these interventions are able to generate economic incentives to reward non-deforestation behaviour, including guaranteed access to markets for whatever productive alternatives are promoted. Encouraging processes that are not capable of delivering change can be counterproductive and demotivate local actors (Brandão et al., 2020). Multistakeholder processes are probably less likely to be effective in contexts where deforestation is driven by frontier expansion processes, especially if these are not driven by smallholder encroachment.

6.6. The role of value chain projects

In our case study, value chain projects were ineffective in reducing deforestation (0.99, TC6). Whereas disseminating production practices delinked to deforestation and attracting market incentives for deforestation-free commodity production could be seen as an intuitive way to halt deforestation, our findings showed that is not necessarily the case. These initiatives are unlikely to play a meaningful role in frontier areas, or in contexts of limited law enforcement and unfavourable political scenarios. This suggests that intensification/land-sparing strategies do not necessarily induce deforestation reductions (Garrett et al., 2018). Importantly, these initiatives may carry the risk of exacerbating deforestation, as observed in the case of cattle ranching (Müller-Hansen et al., 2019). By raising per-hectare productivity, it is at least questionable that farmers would be satisfied with their current income (the ‘full belly’ assumption) and would not consider expanding and deforesting new areas if there are open access forests (the ‘maximize *Homo economicus*’ theory) (Angelsen and Kaimowitz, 2004). This can happen either directly or indirectly through demographic or migratory changes. An illustrative example of indirect land use change is the case where increased yields from soybeans in various regions of Brazil have led to the appreciation of land values, thereby driving land cover changes in the Amazonian frontiers (Richards et al., 2014). While our analysis does not evaluate in detail the reasons for failure (this can be attributed to specific business model design features, implementation gaps, poor corporate incentives or lack of synergies with other interventions), we do suggest carefully considering the locations where these initiatives take place, and their interaction with other interventions to halt frontier expansion. This is particularly relevant since value chain projects, led by NGOs, are currently a popular approach to promote large-scale change through their adoption by private or state actions (Lambin et al., 2020).

7. Conclusions

7.1. Synthesis of findings

This paper has assessed the effectiveness of six interventions to halt deforestation using a Bayesian process-tracing or ‘diagnostic’ approach to theory-building and testing. This approach allowed us to break down their effectiveness under nine theory components over three periods of time. We were able to trace several causal mechanisms linked to a series of interventions with varying levels of success, and we came out of the process practically certain that four theory components are true and reasonably certain or highly confident that four other theory components are true. While eight of our mechanisms explain the outcomes very well, one has left us more doubtful and thus we are keen to refine it in the future, in the direction of either confirmation or refutation, or to develop other mechanisms that are more strongly supported by empirical evidence, as more evidence becomes available.

Our findings offer four important implications for global debates. First, it is important to conceptually distinguish among the types of actors targeted (e.g., smallholder or medium-to-large landholders) and connect that to specific deforestation drivers. Second, it is also key to understand the frontier status (i.e., whether interventions take place in active frontiers or in consolidated areas), since impacts can be contradictory. Third, interventions may be well implemented for a certain period but can lose effectiveness over time, in particular if these do not have adaptive management capacity. Fourth, our findings call attention to synergies among interventions, and in particular to the combination of regulatory interventions to halt frontier expansion with market-based approaches to incentivize non-deforestation behaviour. As we explain above, when deforesting behaviour is “attacked” on multiple fronts, it becomes virtually impossible for the deforester to overcome all these barriers at the same time.

7.2. Final reflections

We propose that this paper offers a methodological contribution to impact assessment studies. The approach implemented here was able to explain outcomes and describe causal mechanisms with considerably high internal validity by putting together the best of both qualitative and quantitative evidence. On the one hand, it managed to avoid some of the typical weaknesses of qualitative evaluation. By assessing theory components against packages of evidence in a transparent and replicable way that is similar to quantitative methodology assessments, it minimizes the risks of confirmation bias and conservatism. On the other hand, it was able to explain outcomes and processes in a rich and detailed way, while also managing to capture complex adaptive dynamics that have been black-boxed in typical quantitative assessments. Another advantage of the Bayesian framework is that its data requirements are looser than for most quantitative methods, and evidence can easily be incorporated as it becomes available.

Despite the potential of this approach, we also identified important shortcomings. For example, we identified difficulties in dealing with external factors that shape the way interventions are implemented, such as broader political changes or narratives. Moreover, this approach is limited when it comes to external validity; although we have high levels of confidence for most of our theory components, we were not able to comprehend the extent to which our conclusions were case-specific. However, as discussed elsewhere (Meyfroidt, 2015, p. 5), “a theory never relies on a single study to establish its validity, rather multiple pieces of evidence of causal effects and mechanisms have to be accumulated from various studies to slowly build confidence." We invite others to test this approach in different geographies and case studies, in order to improve upon, or refute our observations. It is our hope that this research represents a contribution towards a broader and generalizable theory on how deforestation can be effectively tackled.

CRediT authorship contribution statement

Soares-Filho Jaílson: Data curation, Software, Visualization. **Befani Barbara:** Conceptualization, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Brandao Frederico:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing. **Garcia Edenise:** Data curation, Validation, Writing – review & editing. **Rajão Raoni:** Validation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.landusepol.2023.106866.

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